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G.E.C. LIGHTING AT THE ROYAL FESTIVAL HALL.

The G.E.C. at the Festival of Britain

By A. L. PAGET, A.C.G.I., B.Sc.,
Technical Editor of the G.E.C. Journal.

INTRODUCTION.

THE Festival of Britain 1951, which was opened by His Majesty the King on May 3rd, has been promoted to display the contribution to civilisation which Britain has made in the arts, in science and in industrial design. The centre-piece of the Festival is the Exhibition on the South Bank of the Thames. The upstream sequences illustrate the history of the land of Britain and all that the British people have derived from it. They deal broadly with power, industry, design, research, shipyards and fisheries, transport and communications. The dominating feature is the Dome of Discovery, within which is told the proud story of British pre-eminence in discovery and exploration.

The section downstream is concerned with the people themselves, in their homes and on the land ; with their craftsmanship and recreations, their social achievements and their continuing tradition as exemplified, for instance, in the design of clothes, pottery, books, furniture and so forth.

Although London is naturally the centre of the Festival, the exhibition is not confined to the Capital. Condensed versions are travelling throughout the length and breadth of the land. One is mounted in the escort carrier, H.M.S. " Campania ", the other is visiting inland centres.

The great drama of British achievement is further portrayed by the exhibition at the Science Museum, South Kensington, by the " live " exhibition of architecture at Poplar in East

Fig. 1.—The Royal Festival Hall and general illumination of part of the downstream area.

London, and by the commemorative display of the Great Exhibition of 1851 and the exhibition of British books at the Victoria and Albert Museum. Outstanding achievements in the "heavier" fields of science and technology are to be seen at the Kelvin Hall, Glasgow.

Small communities all over Britain are also playing their part. Many hundreds of local authorities have organised displays representative of their history and traditions.

Equipment of G.E.C. manufacture, constituting, in all, more than fifty exhibits, has been accepted for display in many sections of the Exhibition on the South Bank. In every case the criterion has been that the article selected shall be typical of the best in its class and shall combine functional efficiency with excellence of design.

Fig. 3.—Floodlit exterior of the Introductory Pavilion to the Homes and Gardens Building, with illuminated trees and flowerbeds.

Fig. 2.—The bandstand encircled by an array of illuminated flagstaffs.

THE ROYAL FESTIVAL HALL.

The most imposing feature of the Festival of Britain is undoubtedly the Royal Festival Hall which, as the only permanent building on the site, will be a lasting monument to the Exhibition of 1951.

The whole of the main lighting of the auditorium was entrusted to the G.E.C. The ceiling is illuminated by cold cathode fluorescent tubes concealed in nine alcoves spanning the width of the Hall and a large number of 150 watt lamps in dispersive reflectors inset in the ceiling. The alcoves each contain a triple line of tubes, the total length, including the lighting under the gallery, being 3,000 feet. All the cold cathode tubes are arranged for dimming. By careful attention to circuit design a high ratio of dimming has been achieved.

Fluorescent lamps have been installed throughout the rest of the building, and exterior

floodlighting has been provided for the upper parts of the frontage and sides.

SITE ILLUMINATION.

The Company has executed the lighting for that section of the site which contains the Administration Building, on the roof of which is a floodlit flagstaff, visible from a great distance, and on which the effect of apparent rotation is produced by successively switching on and off the floodlights. Another unusual feature of this area is the decorative screen of brightly coloured fibrous spheres suspended by wires from tall masts erected on a boundary wall. Mounted on the masts, 30 high-power floodlights under the control of dimmers, provide continuously changing illumination of the screen. Small fittings on the masts, housing eleven 150 watt spotlights, illuminate the roadways and exits. Decorative coloured panels on the footbridge approach alongside Hungerford Bridge, and on the roadway below, are each floodlit by two units in a diaboloid housing.

In general, the area has been laid out to provide a restful atmosphere, having gardens and lawns in the centre decorated with illuminated shrubs and other features. Nine floodlit flagmasts on the terrace of the Lion and Unicorn Building form an effective ensemble when seen against the night sky. The two masts on the roof of the Restaurant are floodlit by units mounted on the roof.

Perhaps the most striking of the floodlit buildings in this area is the Approach Pavilion to the Homes and Gardens Building, two walls of which are patterned and so lighted as to accentuate the variations of colour. Yet another original effect has been achieved in the floodlighting of the Telekinema Building with its red walls decorated with metallic studs. Inside the building, the proscenium arch and screen are outlined by cold cathode tubing.

The Homes and Gardens Building and its surroundings naturally excite a great amount of general interest. On the end wall there is an exterior mural lit by seven 1,000 watt floodlights; inside, the model kitchen layout is brilliantly illuminated by five shop-window type, 4-lamp fluorescent fittings and eleven dispersive reflectors housing 200 watt lamps. Similar reflectors are used with the eighteen 150 watt lamps which light the display of kitchen equipment.

Other lighting schemes of interest include the ceiling of the Lion and Unicorn Building on which is imposed a lattice-work pattern of English oak, lit from below by fourteen inverted reflectors, each holding a 1,000 watt tungsten lamp.

Inside the lift which serves the Observation Tower indirect cornice lighting is used. Ten 2 ft., 40 watt fluorescent tubes are employed, so

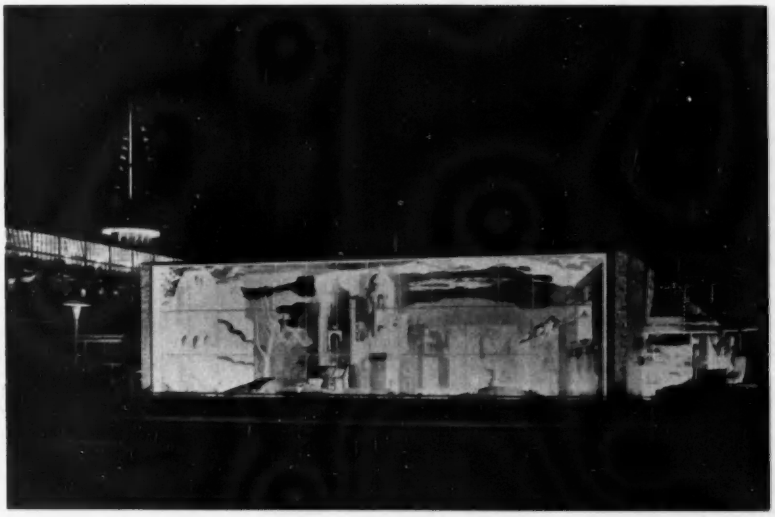

Fig. 4.—Illuminated mural decoration on the Homes and Gardens Building.

Fig. 5.—Façade of Waterloo Station and the Festival Lion.

arranged that no means of support are visible.

Colour matching tubes are used for illuminating the three murals inside the Television Building, and for this purpose are mounted in special trough reflector fittings.

The lighting under Hungerford Bridge embodies a variety of complementary schemes. The ceiling carries a coloured panel illuminated by high-pressure mercury vapour lamps. One wall carries nineteen bulkhead fittings which are so disposed as to form a decorative feature and also serve to illuminate the roadway. On the opposite wall are six elliptical angle fittings containing 150 watt tungsten lamps. Beyond the bridge is a poster board lit by five similar fittings.

Numbers of illuminated bollards are used for lighting the junctions of pathways. "Mushroom" fittings provide general roadway lighting; six of these units, mounted on a wall, illuminate the Terrace of Great Men. Flowerbeds are lit by "Harebell" units and various angle fittings, and groups of flowerpots are illuminated by mushroom lights placed at the centre.

For the main fountains along the river front a continuously changing colour scheme has been devised, making use of 500 underwater floodlights. In all, nearly 1,000 under-water floodlights of a new design have been installed for the illumination of ponds and fountains throughout the site.

DOMESTIC EXHIBITS.

In the Royal Pavilion, which is reserved for the use of the Royal Family and distinguished visitors, a G.E.C. refrigerator of 5·3 cu. ft. capacity is installed; another of

Fig. 6.—The illuminated fountains and underwater lighting.

these refrigerators is on view in the Homes and Gardens Exhibition. Also in the Royal Pavilion there is a 15-gallon cistern type water heater giving an instant supply of hot water at every tap.

The domestic exhibits in the Land Travel Exhibition include a surface type " Mutac " switch, an 8-inch rubber bladed fan, a cooking plate and cooker control unit. There are also, for the purpose of comparison, two electric irons side by side : one dating from 1913, the other a modern streamlined model.

On the aircraft carrier " Campania " the three domestic exhibits are a modern automatic toaster, the latest model domestic electric cooker, and an all-insulated electric hairdryer. In the Power and Production Pavilion are shown two ceiling lighting fittings executed in bronze and chrome, and in the Homes and Gardens Pavilion, there is a display of decorative fairy lights.

INDUSTRIAL EXHIBITS.

Dairy Equipment.

In the Country Pavilion an electric storage steam raiser can be seen in operation with a 19 cu. ft. lagged dairy sterilising chest. It is specially designed for use where steam is required only infrequently and is particularly suitable for dairy farms for sterilising recorder milking plant and for supplying hot water for washing the equipment and utensils. By virtue of its low electrical loading, the steam raiser may be used on mains which would be overloaded by a directly heated appliance.

In the Festival of Britain Farm at Castlereagh, Northern Ireland, there is a chest, directly heated electrically, for sterilising dairy utensils. A sack hoist has also been installed, and part of the floor in the piggery is equipped with low voltage floor warming which is found most beneficial when farrowing is in progress and also to growing pigs. A 3 kW unit type fan heater protects the potato store against frost. A similar heater has also been installed in the workshop.

Fig. 7.—Humber Lifeboat illuminated by underwater floodlighting.

Industrial Lighting.

Of the two industrial lighting fittings on view, one, in the Power and Production Pavilion, is a typical dust-proof fitting for use on motor buses. The cover is of reeded " Perspex " with opal end-pieces and a frame of cast aluminium alloy.

The other, in the National Resources Pavilion, is specially designed for mines roadway lighting and employs a 20 watt lamp. The body is of sheet steel, rust proofed and finished in grey. The cover is of clear " Perspex " with opal ends.

Layer Thickness Meter.

A composite display in the Dome of Discovery demonstrates the principle and application of the layer thickness meter which will be of considerable use in many industries, as it enables direct readings to be taken, in a few seconds, of the thickness of any non-ferrous layer, such as plating, leather, cloth or paint, on the surface of any magnetic material.

STREET AND STUDIO LIGHTING.

Three street lighting lanterns can be seen in the Transport and Communications section : the " Univer-

sal Dioptrion" lantern for main road lighting, the small "Oxford Lantern" for side road lighting and a small sodium lantern for side street lighting. The first of these is an attractive streamlined lantern comprising two dish-shaped prismatic glass reflectors with a die-cast light alloy body.

Also in this section are to be seen several studio lights comprising four 500 watt incandescent "spots", two 2½ kW compact "spots" and one 10 kW "spot."

FLOODLIGHTING OF BUILDINGS

As part of the Festival celebrations many well-known buildings are being floodlit, most of them being visible from the South Bank. The more prominent of these include St. Paul's Cathedral, Carmelite House, Unilever House, Shell-Mex House and the Institution of Electrical Engineers. The new buildings at New Scotland Yard are also floodlit. For all of these, floodlighting equipment has been supplied by the Company.

Fig. 8.—The floodlit dome of St. Paul's Cathedral.

Fig. 9.—Floodlit exterior of the Institution of Electrical Engineers.

FESTIVAL PLEASURE GARDENS.

The Company has been responsible for much of the floodlighting and decorative lighting throughout the Festival Pleasure Gardens and Fun Fair in Battersea Park. In the Main Vista Arcade, executed in the style of the Regency period, the shops are illuminated by fluorescent tubes and tungsten lamps. Similar lighting is used for the shops which border the Main Carriageway. For the shop windows and display lighting reflector fittings have been extensively employed.

Among the most arresting schemes of floodlighting are those illuminating the figures and features on the Fun House and Rest Pavilion. The 450 floodlights employed throughout the Gardens range in size from 1,500 to

100 watts and are all equipped with green, amber, red or blue colour screens. Some of these were specially designed for attachment to units with domed front glasses. Those used for the Fun House are ingeniously concealed in square pillars some distance from the building. The floodlighting of trees has been executed by mounting the lights in the trees themselves so that a most attractive effect is obtained from the light filtering through the foliage.

The Emett Railway naturally appeals to the young people and here the floodlight on the station has been arranged to flash intermittently.

The many thousands of Osram lamps installed throughout the Gardens cover a great variety of types and sizes which include 500 watt projector lamps, mercury, sodium and fluorescent lamps, twisted candle, internally colour sprayed and 3 ft. architectural lamps. In many instances chains of coloured pygmy lamps, hanging in festoons, have been used to give a festival air to the exterior of the various buildings.

COMMUNICATIONS.

The Company's communications exhibits comprise telephone and radio equipment. Two items of telephone equipment are being shown, one being a working model of a rural automatic exchange, the other a small inter-office telephone system, the Gecophone Junior, which is included in the Land Travelling Exhibition. The former, which is in the Transport and Communications section, shows what happens in an automatic exchange when a call is made, and includes equipment as manufactured and supplied by the Company to the British Post Office. The Gecophone Junior can accommodate any number up to six stations ; calls are made by the simple action of pressing a push button. The telephone, which is suitable either for desk or wall mounting, is available in black or ivory moulded plastic.

The radio exhibits include an interesting example of a 1923 crystal receiver which was one of the early commercial radio products of the Company. The contrast is shown by comparison with a modern high-grade communications receiver incorporating the latest refinements of receiver technique. Another more recent activity of the Company in this field is typified by a heavy duty V.H.F. transmitter/receiver specially designed for installation on a locomotive or in similar arduous conditions.

There is also a model of one of the television repeater station towers used in the London-to-Birmingham radio relay link which enables London programmes to be broadcast in the Midlands and vice versa. In addition a contactless aerial switch is shown as an illustration of the advanced technique necessary for this type of project. All these exhibits are on display in the Transport and Communications section, while in the Dome of Discovery there is a V.H.F. radio telephone receiver which has been chosen by the Council of Industrial Design as typical of equipment developed for tropical service.

RESEARCH.

The Research Laboratories of the G.E.C. have provided three exhibits concerned with magnetron oscillator valves. The first is the historic magnetron, which was the first experimental sample of the first type of cavity magnetron to be used in radar (fig. 11). It was the type from which all magnetrons used in radar during the recent war were developed. Another sample made at the same time was sent to the United States with the Tizard Mission in August, 1940. This sample was there tested and copied and in its turn set in motion a train of development in America. This valve operated at 10 kV and 10 amperes and gave powers of 5 to 10 kilowatts at about 10 cm. wavelengths when pulsed with short pulses of about one-millionth of a second duration.

The second exhibit is a modern high-power magnetron (fig. 12). This valve illustrates the big advance in peak power which has been achieved since the original experimental valves ; it gives peak powers of 2 MW at the same wavelength of 10 cms. For demonstration purposes, this valve has been sectioned so that the component parts and methods of construction can be seen. The cathode is mounted on long glass seals, which have to withstand the anode voltage of 40 kV. The power is taken from a slot in the back of one of the cavities and is radiated through a glass dome into a circular waveguide.

The third exhibit is a model which has been built at the Research Laboratories of the G.E.C. to illustrate the operation of a high-power pulse magnetron. In fig. 13 eight resonant cavities of a copper block magnetron are seen round the outside. Electronic currents, indicated by flashing lights, round the backs of the segments give rise to alternating positive and negative polarities on the tips of the segments, each segment being illuminated alternately by green and red lights as its polarity changes. In the centre of the model is the cathode from which proceed electrons, represented by successively flashing lights. These electrons perform orbits in the space between the anode and cathode, and it is shown that electrons starting at a favourable moment give up energy to the electromagnetic field, while those emitted at an unfavourable moment are

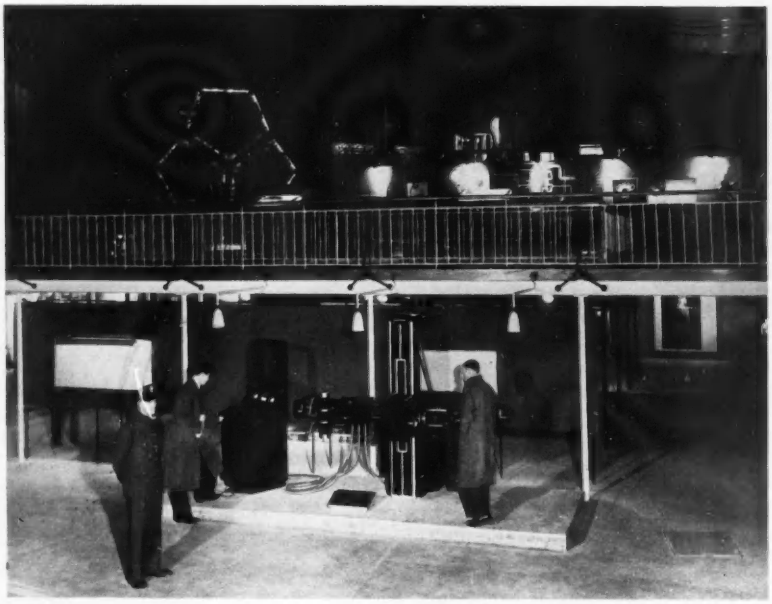

Fig. 10.—Cine-radiography equipment, manufactured by Watson & Sons (Electro-Medical) Ltd., on display in the Dome of Discovery at the South Bank exhibition of the Festival of Britain.

accelerated back to the cathode. The effect of the electromagnetic field from the segments is to focus the electrons into four rotating pencils, or spokes, which become more clearly defined as the anode is approached. The space-charge cloud is illustrated by a rotating spoke-shaped shadow (not seen in fig. 13) in which the individual orbits appear.

There are also two exhibits demonstrating part of the London-Birmingham television radio relay link. The first is a 900 Mc/s oscillator feeding two small festoon lamps alternately through an aerial switch. The U.H.F. switch is arranged to change direction every few seconds, and in order to demonstrate that the lamps are energised by U.H.F. power, one end only of each is connected to the switch, the other ends terminating in short lengths of wire.

A large number of different types of 900 Mc/s tuned circuits is thus demonstrated. The oscillator circuit uses coaxial lines of resonant length, the anode line being $\frac{3}{4}$ wavelength long and the cathode circuit $1\frac{3}{4}$ wavelength long. The feedback from anode to cathode is taken through a tuned circuit formed by a resonant cavity. The U.H.F. switch operates by changing the termination on $\frac{1}{2}$ wavelength stubs, placed along the coaxial lines at points which are themselves $\frac{1}{4}$ wavelength apart, and the wires terminating the lamps are also $\frac{1}{4}$ wavelength long.

This oscillator and switch are used in the London-Birmingham television radio relay link, the oscillator as the 900 Mc/s generator at each station, and the U.H.F. switch to connect standby equipment to the aerials if a fault should occur on the working equipment.

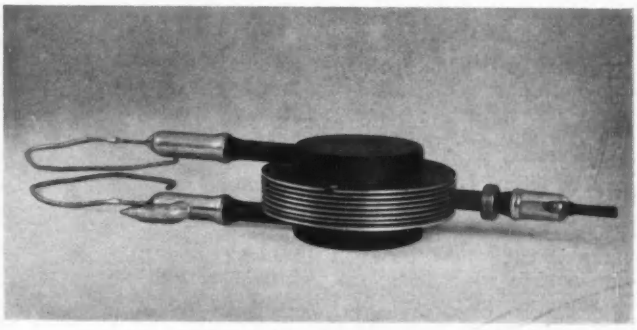

Fig. 11.—Original magnetron made in 1940.

During the first year the link was in use, after the opening of the Sutton Coldfield transmitter, only the equipment for transmitting a programme in one direction at a time had been installed. The direction of the transmission could, however, be reversed by the operation of additional switches of the type shown. The time taken to reverse the whole circuit was only that taken for the one lamp to go out and the other lamp to light up in the demonstration.

Equipment has now been installed for transmission in both directions simultaneously. It is situated, at each repeating station, in a small cabin at the top of a self-supporting tower. A 1/24 scale model of a repeater station is shown in the second exhibit. The cabin at the top of the tower can be plainly seen, with the four paraboloids (two for each direction of transmission) close to it. The towers are 100 ft. high; the small buildings at the foot of the tower contain the power equipment and the stand-by diesel generator.

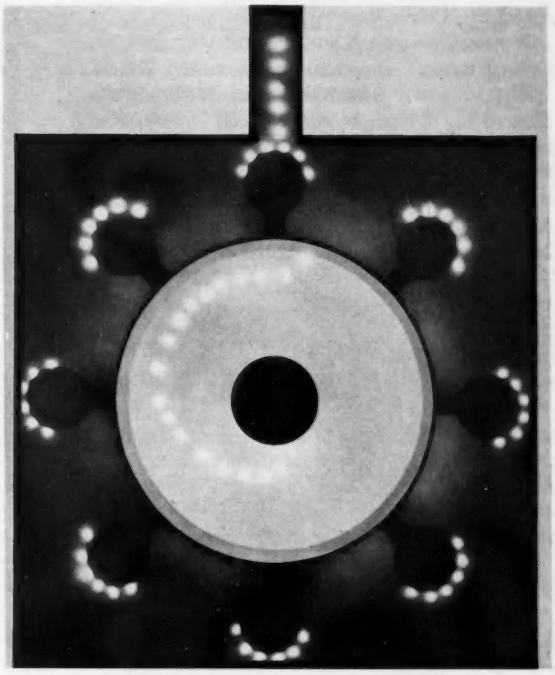

Fig. 13.—Illuminated model illustrating the operation of a high-power pulse magnetron.

THE SCIENCE MUSEUM.

A strikingly original lighting fitting has been made by the Company for the general illumination of the Festival Exhibition at the Science Museum, South Kensington. In keeping with the nature of the exhibits, its form has been inspired by the atomic structure of carbon. More than 600 ft. long, this fitting is composed of fifty-six sections varying in length from 7 ft. to 17 ft. on each of which several groups of five lamps are mounted on "spiders." The spheres at the junctions of sections represent atomic nuclei while the lamps are indicative of the attendant electrons.

Fig. 12.—Modern high-power magnetron.

The general appearance of the fitting is shown in fig. 14, while a complete section is seen in fig. 15. The spheres are 12 ins. in diameter, perforated, and coloured red; each contains two lamps. The lamp-holders on the spiders are enclosed by perforated spinnings, the lamps being white sprayed to minimise glare. The whole of each section is finished a matt white. In all, about 1,800 lamps have been employed.

The various sections are laid out so as to follow the route by which visitors pass through the exhibition. The fitting was designed by the architect of the exhibition, Mr. Brian Peake, F.R.I.B.A.

KELVIN HALL, GLASGOW

A most interesting, and in some ways unique, feature is the fluorescent mural at the Kelvin Hall, Glasgow. Situated at the exit from the Hall of the Future, it will be seen by everyone attending the Exhibition. The mural is 38 ft. wide and 13 ft. high, and is believed to be the largest individual feature to be executed in this way. The artist is William Crosbie, R.A., who has done extensive work in mural decoration. This, however, is the first occasion on which he has employed fluorescent paints, and the Company collaborated closely with him during the experimental stages. As a result, many new and striking colour effects have been achieved.

The theme of the mural is that the sun is the prime source of power, from which have proceeded the natural resources upon which mankind depends. In symbolic form miners are shown at work; two figures are seen paying simple homage for the fruits of their husbandry; fishermen are depicted toiling at the harvest of the sea.

The mural is lit by fourteen 125 watt Osram ultra-violet lamps mounted in suitable reflectors and so focused as to give strong but uniform fluorescence.

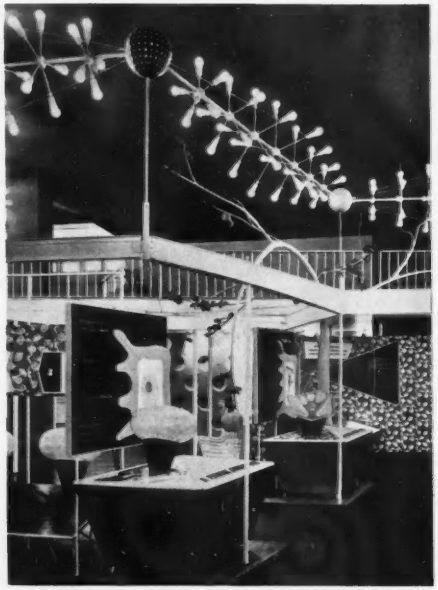

Fig. 15.—Illumination in the Science Museum, South Kensington, showing one complete section of the lighting fitting.

Fig. 14.—General view of the lighting of the Festival Science Exhibition, South Kensington.

EDINBURGH ILLUMINATIONS.

The Festival of Britain celebrations in Edinburgh will very largely coincide with those of the Festival of Music and Drama. During this period a number of historic buildings and thoroughfares will be illuminated, and in many cases G.E.C. fittings have been installed for the purpose.

Fig. 16.—Fluorescent mural at the Kelvin Hall, Glasgow, illuminated by ultra-violet lamps.

The floodlighting of Edinburgh Castle constitutes a most impressive sight which dominates the night skyline (fig. 17).

For the lighting of the walk in West Princes Street Gardens concrete columns with mushroom fittings are employed, while specially designed lanterns have been installed on both sides of the balustrade to provide decorative illumination for the steps leading up to Princes Street.

ADDITIONAL EXHIBITS.

Many of the associate and subsidiary companies of the G.E.C. have had exhibits accepted for display at the Festival.

In the Power and Production Pavilion, Chamberlain & Hookham, Ltd. are showing an induction pattern single pole protective relay for non-directional overcurrent and earth-fault protection. These relays are designed to give (*a*) discriminative protection of transmission lines and distribution networks against faults to earth or between phases, based on the graded time-limit principle, (*b*) "back-up" protection to unit systems, such as the Merz-Price split-pilot system, (*c*) protection of generators, motors, busbars, transformers and so forth against overcurrent and earth-faults.

In the Power Exhibition, Kelvin Hall, Glasgow, the Bushing Company Ltd. have on display a 275 kV terminal bushing.

Salford Electrical Instruments, Ltd. are exhibiting the Radio-Sonde Mark II in the Dome of Discovery. During the war Radio-Sonde was developed in collaboration with the Meteorological Office. The equipment is raised by a balloon to a height of about 65,000 ft. where it measures pressure, temperature and humidity. The instrument consists essentially of a radio transmitter, amplitude modulated by three units, which convert the readings of pressure, temperature and humidity into audio frequencies. Each meteorological unit is successively switched into the modulation circuit and the resulting signal picked up by a radio receiver and the frequency determined by an interpolation oscillator on the ground.

Salford Electrical Instruments Ltd. are also contributing a display of synthetic sapphires and their uses.

The Siemens & General Electric Railway Signal Co., Ltd. have exhibits in the Transport and Communications Section. In the gallery devoted to railway signalling equipment are to be seen an electric point operating mechanism, a long range multi-unit colour light signal, and

a position light shunt signal as used for power signalling installations. Among the road signs and signalling equipment there are a demonstration unit comprising an Autoflex road signal controller, a 5 ft. vehicle detector, and a 2-way 3-aspect signal.

[By courtesy of "The Scotsman".

Fig. 17.—Floodlighting of Edinburgh Castle as seen from Princes Street Gardens.

A particularly interesting exhibit, which is believed to be the only one of its kind, has been provided by Watson & Sons (Electro-Medical) Ltd. The apparatus is capable of making X-ray cinematograph films of any part of the human body. It thus possesses almost limitless possibilities in extending medical knowledge by enabling a leisurely study to be made of the mechanics of moving joints and organs. The high-power generator and rotating anode X-ray tube, in conjunction with a special design of cinema camera and lens, ensure a very high standard of radiographic quality. The apparatus, which was built to the order of the Ministry of Health, has been developed in collaboration with Dr. Russell J. Reynolds.

Sintered Alloys for High-Temperature Service in Gas Turbines

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This paper forms part of the Proceedings of the Symposium on High Temperature Steels and Alloys for Gas Turbines which are contained in No. 43 of the Special Report Series of the Iron and Steel Institute. Acknowledgment is made to the Council of the Institute for their permission to reproduce the paper here.

INTRODUCTION.

THE development of the gas turbine has given considerable stimulus to metallurgical research and to development in the field of high-temperature materials to meet the increasingly severe requirements in overall physical and mechanical properties. Attention must be paid to the development of production techniques which will ensure not only a material consistent in properties, but one which can be manufactured economically in its final form.

The potentialities of powder metallurgy for the production of simple and complex shapes to fairly close dimensional tolerances is well known; equally familiar is the use of the process in the manufacture of metals and alloys of very high melting point and of " compound ", or infiltrated metal components. With the development of high-temperature materials the trend is towards the use of the more refractory metals. Casting and forging problems, however, arise with these alloys at high temperatures, and powder metallurgy may be expected, therefore, to make some contribution to the problem of producing the smaller turbine components near to finished shape and size.

In general, sintered products find application because of some particular and desirable property, usually physical, which is most readily developed by the powder-metallurgy method of manufacture. Published data have shown, however, that for pure metals and pre-alloyed powder, the mechanical properties of the sintered product are much inferior to those of the cast or wrought material because of the inherent porosity of the sintered material. The following methods have been employed to reduce this porosity to a minimum :

(1) Forging the sintered product.
(2) Infiltrating the sintered body with a metal of lower melting point.
(3) Incorporating in the original metal powder a suitable alloying element which becomes molten during the sintering process (" liquid-phase " sintering).
(4) The application of pressure during sintering (hot pressing).

With the possible exception of the cemented carbides, little or no published information is available on the properties of sintered alloys suitable for high-temperature gas-turbine materials. In view of the nature of present-day materials and the trend in the development of new alloys, the infiltration and hot-pressing methods can be expected to play an important part in the powder-metallurgy work in this field, and particularly with regard to the production of finished shapes.

In the work described in this paper an alloy which has been used successfully in the cast state, as a gas-turbine blading material, has been chosen as a standard of comparison. Properties of a sintered alloy of similar composition prepared by a straightforward sintering process are compared with those of the cast alloy.

SCOPE OF THE INVESTIGATION.

The alloy selected for the investigation had a

nominal composition of 64 per cent cobalt, 30 per cent chromium and 6 per cent tungsten, being one of the class of materials generally known as Vitallium. Vitallium in its original cast form contains molybdenum, but information available when this work was started indicated that improved creep-resistance properties were obtainable in the cast alloy when tungsten was substituted for the molybdenum.

Since the work described was initiated a modified Vitallium with a markedly different composition has been developed for high-temperature service. American publications[1-8] describe the high-temperature properties of the cast alloy and give a fairly extensive survey of the effects of ageing and of added elements, including carbon, upon stress-rupture performance at about 800 degs. C. The preliminary work on sintered alloys was confined, however, to the basic tungsten-bearing alloy.

The investigation has aimed at the production of a homogeneous sintered alloy having the lowest possible residual porosity. The presence of a high concentration of the readily oxidisable element, chromium, merely emphasised the need for careful examination of the factors likely to have a bearing upon the sintering process and upon the quality of the sintered product. In preliminary experiments, metallography and density measurements were employed almost solely to indicate the degree of sintering achieved. Later, the scope of the investigation was extended to include room- and high-temperature testing. The tests included preliminary investigations on the effect of ageing and of modifications in composition.

RAW MATERIALS.

Earlier experience with the sintering of similar alloys had shown that the use of elemental chromium in the mixed powders gave rise to porous sinters exhibiting marked heterogeneity in composition. This was attributed to oxide films on the chromium particles, which inhibited both the sintering process and the diffusion of chromium in the alloy.

TABLE 1.

TYPICAL ANALYSES OF MATERIALS USED IN THE PREPARATION OF SINTERED VITALLIUM ALLOY.

	Material	Chemical Composition per cent													
		Co	Cr	W	Al	Pb	Fe	Si	S	C	MnO	Cu	Mgo	Ni	CaO
A	Electrolytic Cr ...		99·2		0·30		0·35	0·17	0·03	0·02					
B	Fine Co	96·6				0·02	0·15	0·14 as SiO_2			0·10 (Mn)	0·36 plus 0·09 as oxide	0·90	1·64	
C	Electrolytic Co ...	99·5					0·10	0·06	0·006	0·025		0·14	Trace Mg		0·04
D	Coarse Co ...	98·8	Trace		0·02 to 0·03 as Al_2O_3		0·20 to 0·30	0·15 to 0·25 as SiO_2	0·02 to 0·04	0·01 to 0·02	0·05 to 0·10	0·05 to 0·10 plus 0·25 as oxide	0·25 to 0·35		0·03 to 0·05
E	57/43 Cr-Co (laboratory alloy)	40·5	57·5		0·20	Trace	0·25	0·15	0·01	0·02		0·15	0·50	0·70	
F	50/50 Cr-Co (commercial alloy) ...	49·7	48·2		0·45		Trace	0·15		0·01 to 0.02	0·15	Trace		Trace	
G	Tungsten			99·1			0·10	0·25 to 0·30 as SiO_2	0·02	0·03					

To reduce this effect chromium was introduced as a powder already pre-alloyed with at least one of the remaining constituents of the required alloy. The chromium-cobalt alloy system shows a probable intermetallic compound Co_2Cr_3, at about 57 per cent chromium-43 per cent cobalt.[9] A "master" alloy of this composition was prepared in the laboratory by induction melting in a magnesia crucible under carefully purified, dry hydrogen. The analyses of the electrolytic chromium and of the cobalt powder B used are given in Table 1. The melt was allowed to freeze in the crucible, the outer skin was ground away to remove any contaminated surface zone, and the ingot was found to break down quite readily to minus 200 B.S.S. mesh powder. The average chromium content of this alloy powder used in the initial experiments was 57·5 per cent.

A bulk supply of commercial "master" chromium-cobalt alloy powder, manufactured by the Thermit process, was, however, used for most of the experimental work mentioned in this article.

The final powder mixture for pressing and sintering was obtained by mixing the "master" alloy with the appropriate quantities of cobalt and tungsten powders. The tungsten powder was typical of that used for the manufacture of lamp filaments, and had a particle size of less than 2 microns. Of the three grades of cobalt powder available (see Table 1), the coarse grade D proved to be the most suitable for use with the commercial "master" alloy. Details of the particle size distribution of the various powders used are given in Table 2.

An experimental batch of mixed powders was never more than 2·5 kilograms, and was prepared by tumbling a mixture of the cobalt, tungsten and chromium-cobalt powders in a sealed bottle, mounted radially on a rotating wheel. A 15-hour mixing time was sufficient to ensure satisfactory homogeneity in the mixed powders.

EXPERIMENTAL TECHNIQUE.

Pressing.

The pressing of the mixed powder before sintering was carried out in hardened steel dies on a single-acting, hydraulically-operated press. The pressings usually took the form of rectangular bars; the two most common sizes used were about 10 mm. square by 110 mm. long and 14 mm. square by 110 mm. long. The smaller bar gave two test pieces, one for tensile and the other for stress-rupture tests; specimens for creep testing were machined from the larger bar.

Sintering Furnace.

A platinum-wound resistance furnace with a mullite sintering tube was used for much of the preliminary investigation. A larger molybdenum-wound furnace which provided a uniformly heated zone of adequate length in relation to the work being sintered, and which could be maintained with the minimum of fluctuation at the sintering temperature for prolonged periods, was designed. Above about 350 degs. C., a molybdenum furnace winding must be protected preferably with hydrogen, and special precautions were taken to prevent contamination of the sintering atmosphere by diffusion of the relatively impure "winding" atmosphere into the sintering tube of mullite.

The temperature requirements were met by suitably spacing and tapping the furnace winding and by feeding the furnaces from a common supply of finely-regulated voltage (a Tirrill regulator). In this way it was possible to maintain a sintering temperature of 1,300 degs. C. or more to within $\pm$ 5 degs. C. for prolonged periods without the use of individual temperature control devices. A close regulation of the pres-

TABLE 2.

PARTICLE SIZE DISTRIBUTION OF METAL AND ALLOY POWDERS.

	Powder	Particle Size Distribution (Frequency)
B	Fine Cobalt	0-1μ, 75% ; 1-2μ, 21% ; 2μ to 3μ (max.), 4%
C	Electrolytic Cobalt	0-10μ, 48% ; 10-20μ, 31% ; 20-50μ, 19% ; over 50μ to 115μ (max.), 2%
D	Coarse Cobalt	0-1μ, 46% ; 1-2μ, 43% ; 2-3μ, 9% ; over 3μ to 5μ (max.), 2%
F	50/50 Chromium-cobalt (commercial alloy)	0-10μ, 71% ; 10-20μ, 20% ; 20-30μ, 5% ; over 30μ to 70μ (max.), 4%
G	Tungsten	0-1μ, 35% ; 1-2μ, 45% ; 2-10μ, 18% ; over 10μ to 45μ (max.), 2%

sure of the hydrogen supplied to the furnace winding and to the sintering tube assisted in maintaining adequate temperature uniformity and control, and helped to prevent contamination of the sintering atmosphere.

heated to 1,000 degs. C. under a continuously pumped vacuum of 10^{-5} mm. of Hg and purified hydrogen was then fed into the sintering tube and maintained static at the slight positive pressure of the hydrogen main for the remainder

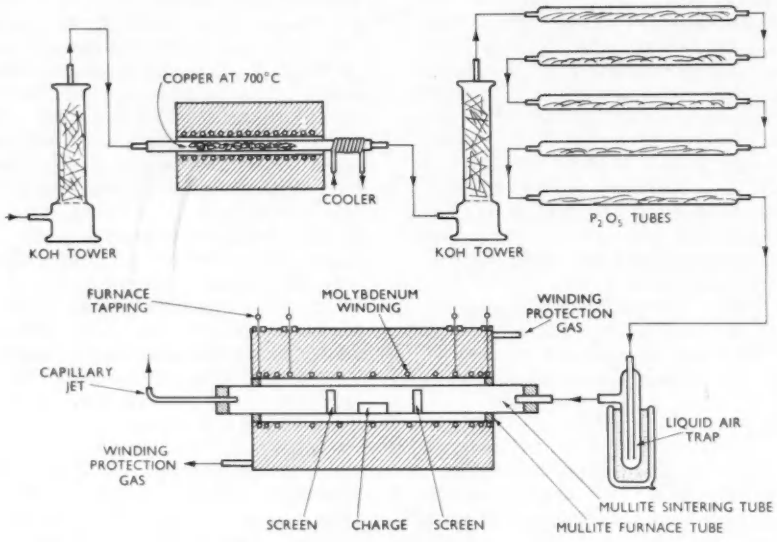


Fig. 1.—Hydrogen purification train.

Sintering Atmosphere.

The sintering atmosphere used throughout the experimental work was purified, dry hydogen. The purification train used is shown in fig. 1. All connections in this train were vacuum-tight, and the final supply line to the sintering tube was of flexible solid-wall metal tubing.

In spite of the careful purification of the hydrogen it was found necessary to screen the work in the sintering tube with pieces of previously-sintered alloy of similar composition. These were positioned in the hot zone upstream and downstream of the charge for sintering, and they removed any residual gaseous impurities in the hydrogen. The hydrogen discharged from the sintering tube was burnt at the end of a long capillary tube to prevent the back-diffusion of water vapour into the sintering zone.

BASIC ALLOY Co – Cr – W.

Preliminary Experiments.

In the preliminary sintering experiments a mixture of cobalt powder B, the 57/43 chromium-cobalt alloy prepared in the laboratory and tungsten fines was used. The pressed bar was of the sintering period and during the cooling stage. In this way it was hoped to eliminate any air trapped in the pressed compact, which would cause oxidation of the mixed powder during heating and would thereby inhibit the sintering process. After a 20-hour sintering at 1,325 degs. C. the best sintered density obtained was, however, only 7·9 g./c.c., as compared with the theoretical value of 8·54. It is possible that the mullite sintering tube was pervious to air under such a high vacuum, and some oxidation of the pressed powder may have occurred during heating to 1,000 degs. C.

All subsequent sintering was carried out in an atmosphere of dry, purified hydrogen flowing slowly and continuously. Under these conditions, and using the same mixed powders as above, after a 20-hour sintering at 1,325 degs. C., test bars having consistent densities of about 8·1 g./c.c. were obtained. The sintered alloy had the following room-temperature mechanical properties :

Ultimate tensile strength	...	40 tons/sq. in.
Limit of proportionality	...	32 tons/sq. in.
Elongation (on 0·625 in.)	...	2 to 8 per cent
Izod impact	...	11 ft. lb.

A stress-rupture test at 650 degs. C., under a loading of 8 tons/sq. in., was discontinued after 1,032 hours.

The comparatively high porosity of the material (fig. 2)* suggested that, with improved density, better mechanical properties might be developed in the sintered product.

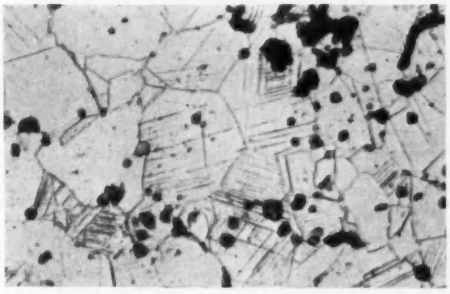


Fig. 2.—Section of original sintered Vitallium alloy; approximate density 810 g./c.c. x 180.

For all subsequent experiments the bulk supply of the commercial chromium-cobalt "master" alloy was used. The alloy powder had a nominal composition of 50 per cent of chromium and 50 per cent of cobalt and was well within the limits for the introduction of the required amount of chromium into the alloy mixture. Details of the analysis and particle size distribution of this powder are given in Tables 1 and 2. The 50/50 alloy had a higher percentage of coarser particles and was not as pure as the original laboratory-prepared alloy, mainly in respect of aluminium content. Subsequent work, however, showed that the level of impurities did not seriously impair the quality of the sintered product.

*Etched with freshly prepared mixture of three volumes of cold concentrated hydrochloric acid and one volume of 30 per cent hydrogen peroxide.

When the new "master" alloy was mixed with cobalt powder B and tungsten fines, it was not possible to obtain pressings which were mechanically strong in the as-pressed, or "green", state. Powder mixtures using the original 57/43 alloy powder had presented no difficulty in this respect, in spite of the absence of a binding agent. This behaviour was apparently associated with characteristics of the various powders which were not apparent in the simple microscopic method of measuring particle size distribution, and a fuller examination of the physical characteristics of the various powder constituents was needed.

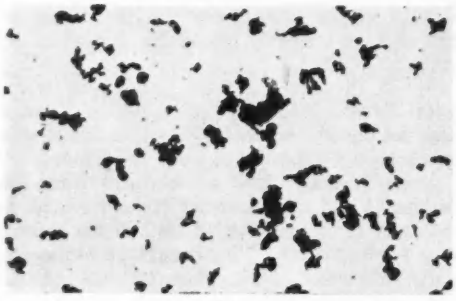
Assessment of Powders.

The three grades of cobalt powder and the two "master" alloys were subjected where possible to a more comprehensive physical analysis on a Haultain Infrasizer[10], and the specific surface of every powder was measured by the air permeability method of Lea and Nurse[11]. These results are shown in Table 3; figs. 3 and 4 illustrate the shape and particle size distribution of the various batches.

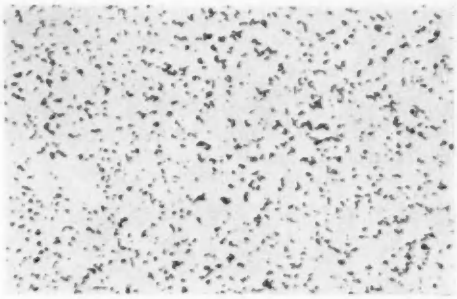
The 50/50 alloy powder contained a much higher proportion of fines than did the original 57/43 alloy (Table 3). Moreover, the cobalt powder B, which had been used in all the preliminary work, was shown also to contain a high proportion of fine particles less than 1μ. From the point of view of "green" strength at least, the combination of fine cobalt powder with fine "master" alloy appeared less favourable than that with the coarser grade of chromium-cobalt powder.

TABLE 3.
HAULTAIN INFRASIZER TESTS

	Powder	Cone Number 1	2	3	4	5	6	Filter Bag	Specific Surface Sq. cm./g.
		Weight, per cent							
B	Fine Cobalt	Test not made because of fire risk							5,837
C	Electrolytic Cobalt	37·7	16·8	14·4	10·7	8·1	4·7	7·6	1,025
D	Coarse Cobalt	3·0	4·1	7·6	9·1	9·3	12·6	54·3	3,490
E	57/43 Chromium-cobalt (laboratory alloy)	41·2	18·3	14·2	11·3	6·5	5·2	3·3	628
F	50/50 Chromium-cobalt (commercial alloy)	13·8	17·7	14·4	11·0	10·0	9·0	24·1	1,450
G	Tungsten	20·4	15·0	22·3	24·5	11·6	5·4	0·8	407



(a)



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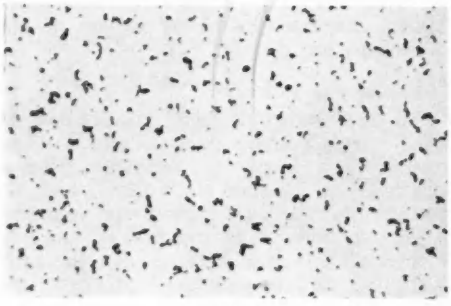


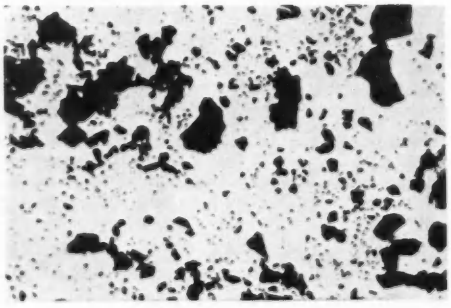
(c)

Fig. 3.—Shape and size of individual particles of cobalt powders x 90: (a) electrolytic C; (b) cobalt B; (c) coarse cobalt D.

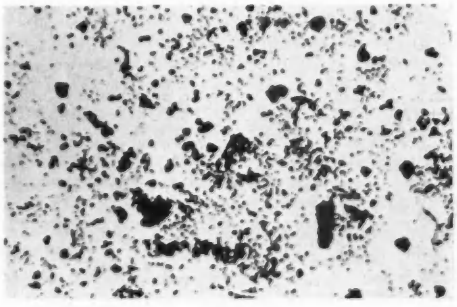
This view was confirmed by a series of sintering experiments on powder mixes made in turn from each " master " alloy powder with each grade of cobalt powder, together with the usual amount of tungsten fines. Certain of these mixes gave mechanically weak pressings in the absence of a binding agent, and therefore all the compacts in this particular series were pressed, using as a binder 1 per cent by weight of camphor in ethyl ether. Adequate purging of the furnace sintering tube with hydrogen while the pressing was held at 150 degs. C. was sufficient to remove all traces of the binding agent from the tube, and it could be shown, provided this was done carefully, that the use of the binder had no adverse effect upon the degree of sintering obtained.

Typical density measurements obtained after a 20-hour sintering at 1,325 degs. C. with sintered bars produced in this way are given in Table 4. The combination of the 50/50 "master" alloy with either cobalt powder B or D gave a marked improvement in density of sintered alloy over the original mixture of the 57/43 " master " alloy and cobalt powder B. Moreover, the combination of cobalt powder D with the 50/50 " master " alloy was one which did not require the use of a binding agent during pressing. This latter combination was therefore adopted as the standard for all further work.

Later supplies of the 50/50 chromium-cobalt alloy powder were found to have considerably lower specific surfaces than the original batch, and resulted in a lower density of the sintered alloy. These batches were therefore subjected

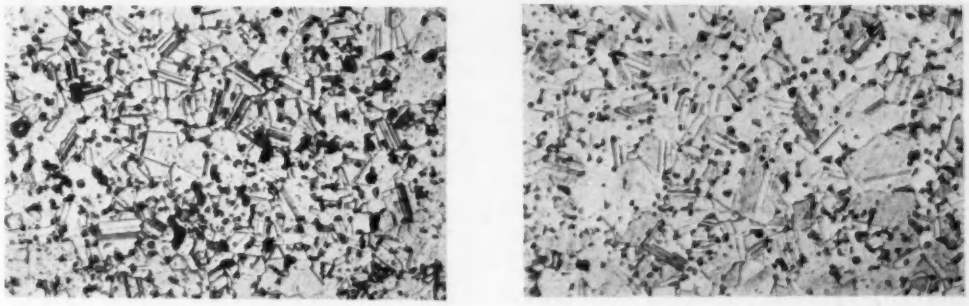


(a)



(b)

Fig. 4.—Shape and size of individual particles of chromium cobalt " master " alloy powders x 90 : (a) 57/43 alloy E ; (b) 50/50 alloy F.



(a) (b)

Fig. 5.—Etched sections of sintered Vitallium alloy, sintered for 8 hours at 1,325 degs. C. in dry, purified hydrogen x 180 : (a) compacted at 15 tons/sq. in. ; (b) compacted at 45 tons/sq. in. Etched with a freshly prepared mixture of three volumes of cold concentrated HCl and one volume of 30 per cent H_2O_2.

to further ball-milling until their specific surfaces were near to that of the original and the density of the sintered alloy showed the previous improvement. The trend in density of the sintered alloy with increasing specific surface of the " master " alloy powder used in the standard mix was as follows :

Specific Surface of 50/50 Alloy Powder, sq. cm./g.	Density of Sintered Product g./c.c.
900	8·34
1,200	8·42
1,448	8·43
1,539	8·44

From this work the following comparative specification of powders for the preparation of the standard basic alloy was formulated :

34 per cent of coarse cobalt powder D, specific surface 3,300 $\pm$ 200 sq. cm./g.

60 per cent of 50/50 chromium-cobalt alloy powder, specific surface 1,440 $\pm$ 20 sq. cm./g.

6 per cent of tungsten powder, specific surface, 400-700 sq. cm./g. (unimportant because of small volume).

Bearing in mind the raw materials commercially available, the following limits were set on the purity of the powders used :

Cobalt	98·5 per cent
Chromium-cobalt	98·0 per cent
Tungsten	99·0 per cent

Preparation of Sintered Alloys.

Compacting Pressure.—The effect of compacting pressure upon the density in the " green " and in the sintered conditions is indicated by the following figures :

Compacting Pressure tons/sq. in.	Density, g./c.c.	
	As pressed	8-hour sintering at 1,325 degs. C.
15	4·95	8·36
25	5·57	8·39
35	5·74	8·41
45	5·91	8·41

The corresponding photomicrographs in figs. 5a and 5b show a matrix of primary solid solution exhibiting considerable twinning, with a uniformly dispersed, rather coarse, second phase which has not been identified. It is probable

TABLE 4.

EFFECT OF DIFFERENT COMBINATIONS OF AVAILABLE POWDERS ON FINAL DENSITY OF SINTERED VITALLIUM.

(Compacting Pressure, 35 tons/sq. in. ; sintering time, 20 hrs. at 1,325 degs. C.)

Chromium-Cobalt Alloy Powder		Cobalt Powder	Final Density of Sintered Vitallium g./c.c.
E	57/43	B	8·05
		C	8·20
		D	8·30
F	50/50	B	8·42
		C	7·85
		D	8·44

Tungsten Powder G used in all cases.

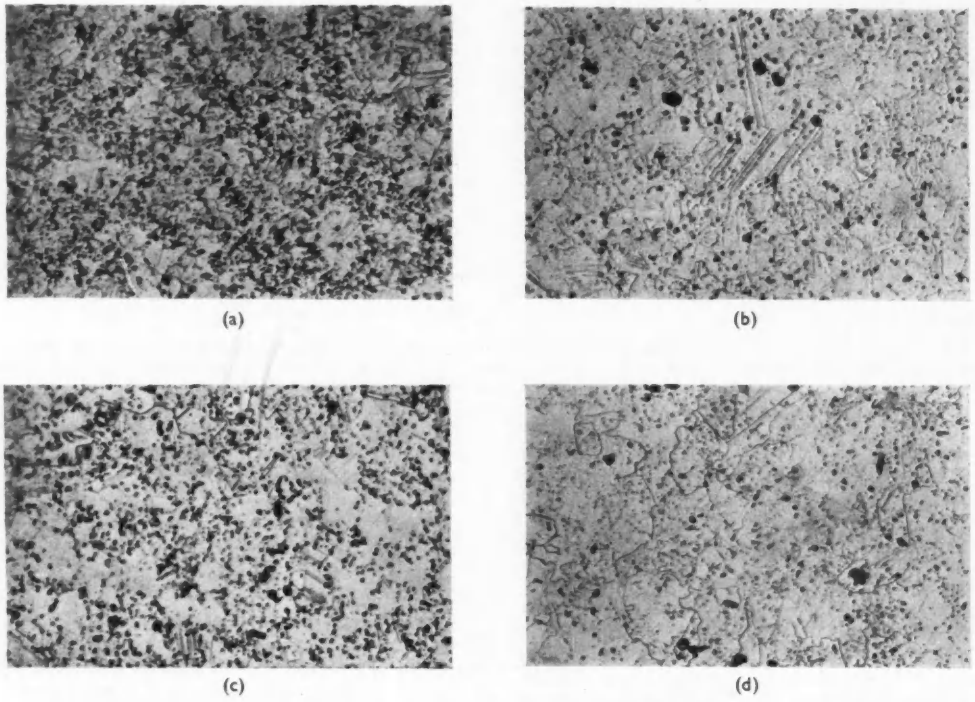


Fig. 6.—Effect of temperature on sintering to give a final density of approximately 8·42 g/c.c. x 90 : (a) 1,275 degs. C. for 20 hours ; (b) 1,300 degs. C. for 12 hours ; (c) 1,325 degs. C. for 5 hours ; (d) 1,350 degs. C. for 2 hours.

that this latter phase arises from the impurities in the raw materials used in the preparation of the alloy.

The above figures show that there is no improvement in sintered density at compacting pressures in excess of 35 tons/sq. in. ; this pressure was used in all the subsequent work. With the standard mixture of powders, this pressure was sufficient to give compacts which were mechanically strong without the use of a binding agent.

Temperature and Time of Sintering.—The effect of sintering temperature and time of sintering in purified, dry hydrogen upon the density of the sintered alloy is shown in Table 5. The maximum density achieved was about 8·42 to 8·44 g./c.c., i.e. almost 99 per cent of the theoretical value. This maximum was obtained with various combinations of temperatures and times : 20 hours at 1,250 degs. C. gave a similar density to 12 hours at 1,300 degs. C. or to about 5 hours at 1,325 degs. C. With a sintering temperature of 1,325 degs. C., there is little advantage in extending the sintering time beyond 5 hours ; for the preparation of specimens for the measurement of room- and high-temperature properties (pp. 148 to 153), however, a standard sintering time of 8 hours at 1,325 degs. C. was selected to allow sufficient time for diffusion and the attainment of a homogeneous alloy.

The photomicrographs in fig. 6 show that the sintering temperature has a marked effect upon the final grain size of the sintered alloy. The matrix structure, which tends to be heavily masked by the second phase, has a grain size which progressively increases with increasing temperature. Increasing sintering temperature also favours the dispersion of the second phase, which, although present primarily as a grain-boundary constituent at the lower sintering temperatures, is well dispersed throughout the grains in the alloys sintered at 1,325 degs. C. and 1,350 degs. C.

Increasing the time of sintering at 1,325 degs. C. from one to 12 hours results in a progressive decrease in porosity and, as shown in fig. 7, an improvement in the overall distribution of the

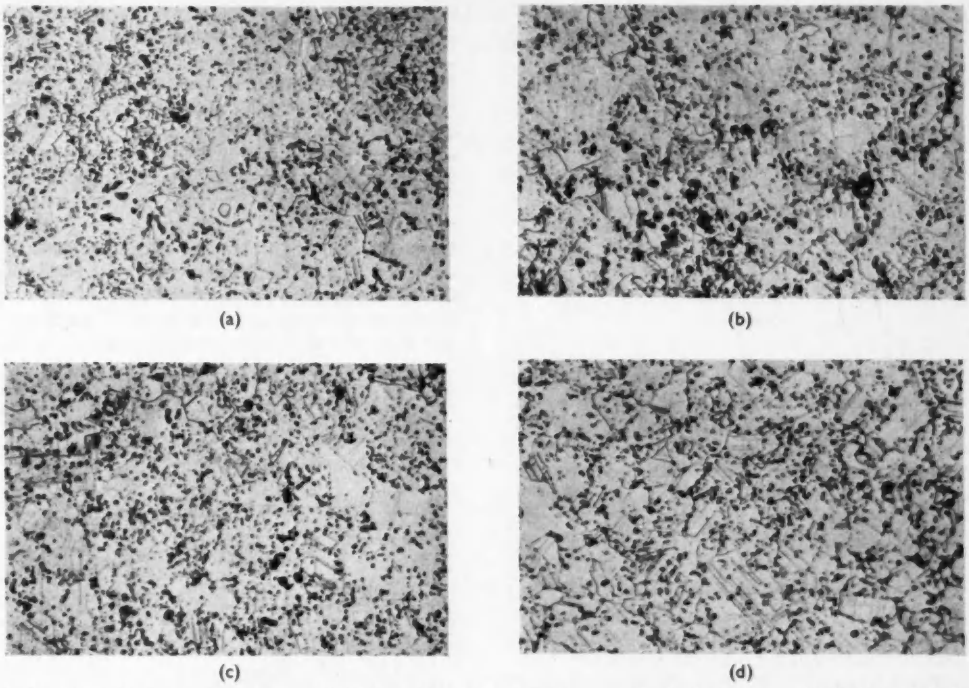


Fig. 7.—Effect of time on sintering at 1,325 degs. C. x 180 : (a) 1 hour : density 8·32 g./c.c. ; (b) 2 hours : density 8·38 g./c.c. ; (c) 5 hours : density 8·41 g./c.c. ; (d) 12 hours : density 8·43 g./c.c.

second phase, which, at the shorter sintering times, has a tendency to segregate, indicating inadequate time for interdiffusion of the alloying elements and for homogenisation.

PHYSICAL PROPERTIES.

Table 6 gives the physical properties which have been determined for the sintered alloy, together with the limited published data on the nearest equivalent cast alloy, Haynes Stellite No. 23. The thermal expansion data are of particular interest. Fig. 8 shows the dilatation curve for the as-sintered alloy with an inflexion within the temperature range of about 750 degs. C.—900 degs. C. Grant and Lane[7] have reported a similar phenomenon in cast alloys,

TABLE 5.

EFFECT OF SINTERING TEMPERATURE AND TIME OF SINTERING ON FINAL DENSITY OF VITALLIUM ALLOY

(Compacting Pressure, 35 tons/sq. in.)

Sintering Time, hrs.	Sintering Temperature and Density, (g./c.c.)				
	1250 degs.C.	1275 degs.C.	1300 degs.C.	1325 degs.C.	1350 degs.C.
1	—	—	—	8·32	8·35
2	—	—	—	8·38	8·41
5	8·34	8·37	8·38	8·41	8·42
12	8·38	8·41	8·40	8·43	8·44
20	8·42	8·43	8·43	8·44	8·44

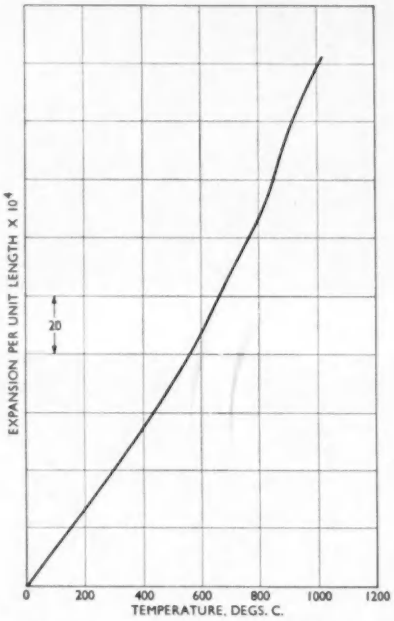


Fig. 8.—Dilatation curve for sintered Vitallium.

including the Vitallium type, and have associated the inflexion with an ageing effect.

Scaling Resistance.

A limited series of scaling tests on the as-sintered material has been carried out by the Research Department of William Jessop & Sons Ltd., Sheffield. Moist preheated air was passed over the heated alloy for a period of 70 hours, and the scaling index was determined by the loss in weight per sq. cm. of surface, after removing the scale by the sodium hydride method. The results are given in Table 7. For comparison, the results of similar tests on an equivalent cast alloy and on steels *R*.23 and *G*.18*B* are given. The sintered alloy is superior in resistance to these steels at all temperatures and is in no way inferior to the cast alloy.

Room-Temperature Mechanical Properties.

The tensile properties of the sintered alloy were determined on a Hounsfield tensometer on machined test pieces, 0·025 sq. in. in section and with a gauge length of 0·625 in. To obtain a direct comparison with cast material of identical composition, similar tests were carried out on specimens from material prepared by melting sintered alloy bars. The latter were gravity-cast at 1,610 degs. C. into moulds preheated to 1,100 degs. C. Details of the results obtained are given in Table 8.

A reasonable variation in sintering conditions to give a material of substantially the same final density had no appreciable effect on the mechani-

TABLE 6.

COMPARISON OF PHYSICAL PROPERTIES OF SINTERED AND CAST ALLOY.

Property	Sintered Alloy	Cast Alloy (Haynes Stellite No. 23)
Nominal Composition	30% Cr, 6% W, 64% Co	28% Cr, 6% W, 2% Ni, 0·25% C, balance Co
Density (g./c.c.)	8·44 (theoretical 8·54)	8·54
Mean thermal expansion in./in./deg.F.x10⁶		
70-1,000 degs. F.	7·95	8·18
70-1,200 degs. F.	8·45	8·48
70-1,500 degs. F.	9·08	9·24
70-1,600 degs. F.	9·27	
70-1,800 degs. F.	9·95	
1,500 degs. F.	9·86	
1,800 degs. F.	11·65	
Electrical resistivity (microhm/cm. at 20 degs. C.)	Approx. 160	
Specific heat (cal./g./deg. C.)	Approx. 0·087	
Melting Point	1,420 degs. C.	
Hardness	320-350 V.P.N. (30-kg. load)	

TABLE 7.

SCALING RESISTANCE

Material	Scaling Resistance (mg./sq.cm.)		
	750 degs. C.	950 degs. C.	1100 degs.C.
Sintered Alloy	0·23	0·90	3·4
Cast Alloy (Haynes Stellite No. 23)	—	—	4·0
*R*23	0·40	2·5	—
*G*18*B*	1·3	9·0	—

cal properties of the as-sintered alloy. By varying the time of sintering a sintered material of satisfactory high density can be obtained over a range of sintering temperatures (see Table 5). In this way it should be possible to prepare specimens of controlled grain size. The room- and high-temperature mechanical properties of alloys of varying grain size, produced in this way, are at present being investigated.

The grain size of the cast alloy specimens, produced by melting sintered alloy, is illustrated in fig. 9. Table 8 shows that the very coarse-grained cast alloy (see fig. 9a) had a markedly inferior strength to the sintered alloy, and that the alloy from heat 1 (see fig. 9b) of grain size only slightly larger than that of the standard alloy sintered at 1,325 degs. C. for 8 hours, had comparable properties apart from a much higher elongation value. The latter is probably associated with the absence of intergranular residual porosity in the cast alloy.

The hardness of the sintered alloy lies between 320 and 350 V.P.N. and is virtually independent of the sintering conditions if the final density is approximately that obtained by the standard sintering schedule, i.e. 8·42 g./c.c.

High-Temperature Properties.

Creep Properties.

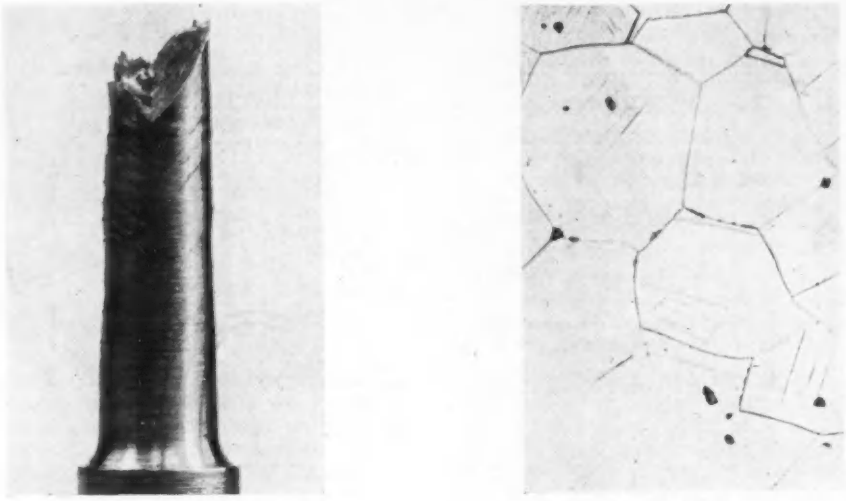
Creep tests at 650 degs. C. and 750 degs. C. on material sintered at 1,325 degs. C. for 8 hours carried out at the National Physical Laboratory are summarised in Table 9. Comparative stress-rupture data for the sintered alloy and those published for Haynes Stellite No. 23 are given in Table 10.

TABLE 8.

ROOM-TEMPERATURE PROPERTIES OF SINTERED AND CAST BASIC ALLOYS AND EQUIVALENT HAYNES STELLITE ALLOY

Material	Density g./c.c.	Ultimate Tensile Strength tons/sq.in.	Limit of Proportionality tons/sq.in.	Elongation per cent	V.P.N., 30 kg. load	Izod Impact Value ft. lb.
Standard alloy sintered 8 hr. at 1325°C.	8·42	44·6*	35·5*	6·1*	340-350	8
Standard alloy sintered 12 hr. at 1,300°C.	8·42	44·8*	30·7*	7·2*	330-340	—
Standard alloy sintered 5 hr. at 1,325°C.	8·41	47·1*	34·8*	7·2*	320-330	—
Alloy cast from melted sintered bars : Heat 1	8·46	27·5†	23·0	17·5†	—	—
Alloy cast from melted sintered bars : Heat 2	8·54	44·5 42·5 39·0	31·5 35·5 29·0	13·5 12·0 12·0	—	—
Equivalent cast alloy (Haynes Stellite No. 23)	8·54	49·5*	23·5*	8·7*	—	—

* Mean values.
† Large grain size ; marked slipping between grains.



(a) (b)

Fig. 9.—Material cast from sintered Vitallium alloy bars.
(a) Fractured tensile test-piece (see Heat 1, Table 8) x 200. (b) Etched section (see Heat 2, Table 8) x 200.

In general, the creep properties of the as-sintered alloy, are low in comparison with those quoted for the nearest equivalent cast alloy. What contribution the carbon content of the latter makes to the creep resistance of the alloy is speculative, but Grant[1, 2] has shown that there is an optimum carbon content, about 1·1 per cent, for alloys of this type, which gives the maximum stress-rupture properties. By extrapolation of Grant's data, a cast alloy containing 69 per cent of Co, 24 per cent of Cr, 6 per cent of Mo, and free from carbon, would have a life to rupture at 815 degs. C., under a load of 13·4 tons/sq. in., of about 7 hours. Comparable figures for the sintered alloy are not available, but at 750 degs. C., under a similar loading, the life to rupture is 13 hours. In the light of these data the creep properties of the as-sintered alloy are encouraging. Comparative creep tests on the alloy as cast from melting sintered bars have yet to be made.

TABLE 9.
RESULTS OF N.P.L. CREEP TESTS ON SINTERED VITALLIUM.

Temperature degs.C.	Stress tons/sq. in.	Time for Specific Creep Strains, hrs.						Time for Fracture, hrs.	Elongation on 1½ in. per cent	Young's Modulus E (from loading curves) lb./sq. in.
		0·1 per cent	0·3 per cent	0·5 per cent	1·0 per cent	2·0 per cent	3·0 per cent			
750	12	0·5	1·8	3·7	9·1	18·9	28·5	29	4·0	Mean value $18{\cdot}0 \times 10^6$
	10	1·0	6·1	12	24·5	42	54	63·5	6·5	
	8	4·0	21	41·5	96	171	—	258	*	
	6	7·0	38	81	187	330	410	534	4·0	
	4	5·0	40	120	380	920	Discontinued after 1,050 hours			
650	12	23	125	224	525	1,080	1,450	1,940	7·0	24×10^6

* Fractured at gauge mark.

Fatigue Properties.

The results of Haigh fatigue tests at 750 degs. C., also carried out at the National Physical Laboratory, are given in Table 11, and are illustrated in fig. 10. The tests were made on 0·22 in. diameter specimens, and at a zero mean stress.

For the standard sintered product at 750 degs. C. the stress for 300 hours' endurance is 0 ± 10·5 tons/sq. in., which compares with a static stress of about 7 tons/sq. in. to produce fracture in creep in the same time. Material of sub-standard density gave a comparable endurance to that of the higher-density alloy.

TABLE 10.

STRESS-TO-RUPTURE DATA.

Material	Temperature degsC	Condition	Stress for Rupture tons/sq. in., in.: 10 hr.	100 hr.	1,000 hr.
Sintered Alloy	750	As sintered	13·5	9·5	5·25
Haynes Stellite No. 23	705	As cast	22·3	17·4	13·4
	760	As cast	—	16·1	11·2

WORKING.

No difficulty has been experienced in the hot-rolling of sintered alloy bars to sheet. The material was heated to 1,200 degs. C. in hydrogen before every pass, and the reduction per pass was approximately 10 per cent.

A survey has been made of the room-temperature mechanical properties of 0·025 in. thick sheet rolled from bar originally of 0·375 in. square section. The average properties obtained were as follows:

Ultimate strength	53·1 tons/sq. in.
Limit of proportionality	23·9 tons/sq. in.
Elongation (on 1 in.)	... 4·9 per cent.
Hardness ...	... 360 V.P.N.
Density before rolling	... 8·44 g./c.c.
Density after rolling	... 8·48 g./c.c.

The effect of heat-treatment of the hot-rolled material upon the room-temperature mechanical properties was also examined and the results are shown in fig. 11. A maximum tensile strength of about 68 tons/sq. in. is developed by a treatment of 2 hours at 800 degs. C. This is probably an ageing effect comparable to that reported by Grant and Lane[7] for as-cast alloys of this type.

AGEING.

Earlier observations on the dilatation characteristics of the sintered alloy and the effect of heat treatment on rolled sheet indicated that the alloy may be susceptible to ageing at temperatures around 800 degs. C. An examination of the effect of ageing on room- and high-temperature properties is in hand, but limited results only are available.

The results of the early experiments on the effect of ageing on room-temperature mechanical properties are summarised in Table 12. With a suitable combination of time and ageing temperature it is possible to increase both the

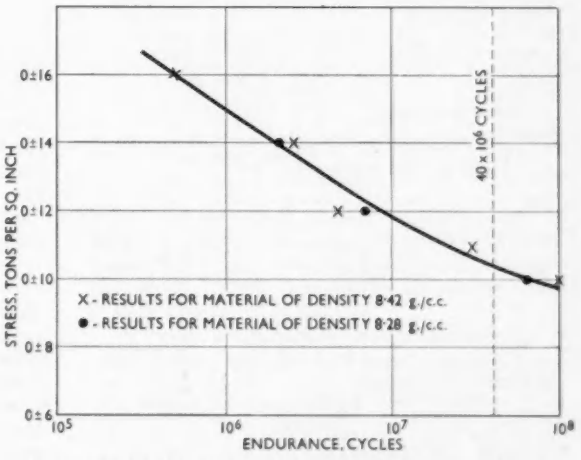


Fig. 10.—Haigh fatigue tests on sintered Vitallium at 750 degs. C.

limit of proportionality and the ultimate tensile strength by about 10 tons/sq. in. with a slight reduction in elongation. The cast alloy prepared from sintered bars, also showed an enhancement in room-temperature strength, but only by about 4 tons/sq. in. above that of the original as-cast alloy.

So far, work on the effect of ageing on creep resistance has been confined to only one experiment. A specimen of sintered alloy, aged at 800 degs. C. for 72 hours, gave a life to fracture at 750 degs. C. under a load of 6 tons/sq. in. of 722 hours with a total elongation of 2·5 per cent. The corresponding values for the as-sintered material were 534 hours and 4 per cent respectively.

Experimental work has indicated that the sintered alloy is extremely sensitive to heat-treatment, and for the maximum strengthening effects of ageing to be obtained, the heat-treatment before ageing and the ageing treatment itself must be very clearly defined. X-ray examinations have shown that the stable high-temperature structure of the sintered alloy is face-centred cubic, and this structure can be retained by rapid cooling from solution temperature above 900 degs. C.

The face-centred cubic structure is metastable at temperatures below about 900 degs. C., and a relatively small amount of cold-work effects complete transition to a hexagonal close-packed structure. Thus, not only do the fractured surfaces of tensile test pieces, originally of the high-temperature structure, show such transition, but the act of sectioning of specimens for metallographic work may be sufficient to cause transformation. Preparation of filings cannot be carried out at room temperature without the phase transition occurring, and for X-ray examination of the transition it was found necessary to reheat filings at the solution temperature and quench. Evacuated silica containers were used successfully for this purpose.

Reheat treatments of these filings have been carried out to make a preliminary survey of the transition. Parallel tests on solid specimens, utilising X-ray surface reflection techniques, proved that the nature of the changes produced in filings was representative of changes in solid specimens. More accurate lattice parameter measurements, however, could be obtained with filings than with the solid specimens.

TABLE 11.

RESULTS OF N.P.L. HAIGH FATIGUE TESTS AT 750 degs. C.

Material	Stress, tons/sq. in.	Endurance, cycles x 10^6
Standard sintered product (8·42 g./c.c.)	0 ± 16	0·504
	0 ± 14	2·528
	0 ± 12	4·564
	0 ± 11	29·410
	0 ± 10	98·428
Low-density product (8·28 g./c.c.) using low-purity Cr-Co alloy powder	0 ± 14	2·010
	0 ± 12	6·644
	0 ± 10	60·474

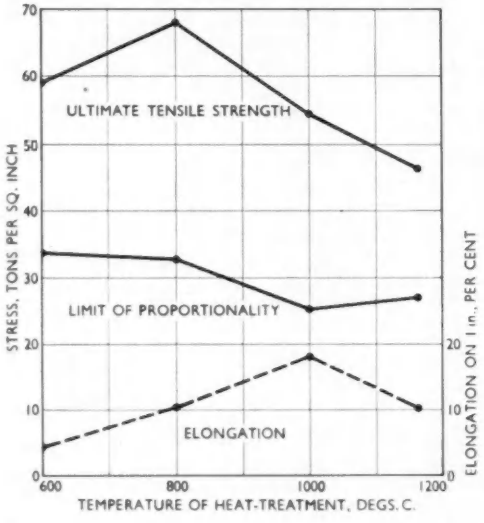


Fig. 11.—Effect of heat treatment on room temperature mechanical properties of sheet hot rolled at approximately 1,100 degs. C. from sintered Vitallium bars. Specimens held at heat-treatment temperatures for 2 hours.

TABLE 12.

EFFECT OF AGEING ON ROOM-TEMPERATURE PROPERTIES OF SINTERED VITALLIUM ALLOY.

Ageing Treatment		U.T.S. tons/sq. in.	L. of P. tons/sq. in.	Elongation on 0·625 in., per cent
Time, hr.	Temp., degs. C.			
48	750	52·5	46·5	4·0
72	750	56·0	47·0	5·0
96	750	50·0	43·0	4·0
24	800	50·0	43·5	4·5
48	800	53·0	43·5	5·0
63	800	52·0	45·0	4·8
72	800	Specimens broke at 40 before yield point		
96	800	51.0	44·5	5·5
15	850	49·0	35·5	6·0
24	850	54·0	41·0	5·5
39	850	47·5	41·0	4·5
52	850	49·0	40·5	5·0
63	850	49·0	41·0	4·5
As sintered		47·5	37·0	6·0

A progressive change from face-centred cubic to hexagonal close-packed structures was effected at 700 degs. C. with increasing times of treatment of the order of a few hours. Treatment for 6 hours at this temperature gave only about 25 per cent of the hexagonal structure, whereas at 850 degs. C. complete transition to the hexagonal structure took place in a few minutes.

MODIFICATIONS TO THE STANDARD ALLOY.

THORIA.

The possible beneficial effects of additions of refractory oxides, such as thoria, in low and well-dispersed concentrations on the high-temperature strength of the sintered alloy have been investigated. Thoria, in the appropriate concentration, was added as a solution of thorium nitrate to the mixture of the constituent powders of the alloy, and after thorough mixing was dried off on a water bath. The nitrate was then converted to oxide by heating at 775 degs. C. in dry, purified hydrogen; this method gave a satisfactory distribution and dispersion of the thoria.

A preliminary survey was made of room-temperature mechanical properties and high-temperature creep resistance of sintered alloys containing 0·05-0·5 per cent of thoria. The results of tests are given in Tables 13 and 14. Within this range of concentration, the thoria had no serious effect on sintering, and satisfactory densities were obtained without difficulty.

Table 13 shows that 0·3 per cent of thoria effects no improvement in room-temperature mechanical properties compared with the alloy without thoria, but that 0·1 per cent increases the limit of proportionality and the ultimate strength fairly appreciably, the elongation being lower in both cases. Creep properties for the 0·3 per cent thoria alloy at 650 degs. C. and 750 degs. C. are inferior to those of the standard alloy, but 0·1 per cent thoria alloys show a useful improvement in life at these temperatures. Data are not yet available on the effects of still lower concentrations, nor on the combined effects of adding thoria and ageing.

Typical structure of an alloy containing thoria are shown in fig. 12.

CARBON.

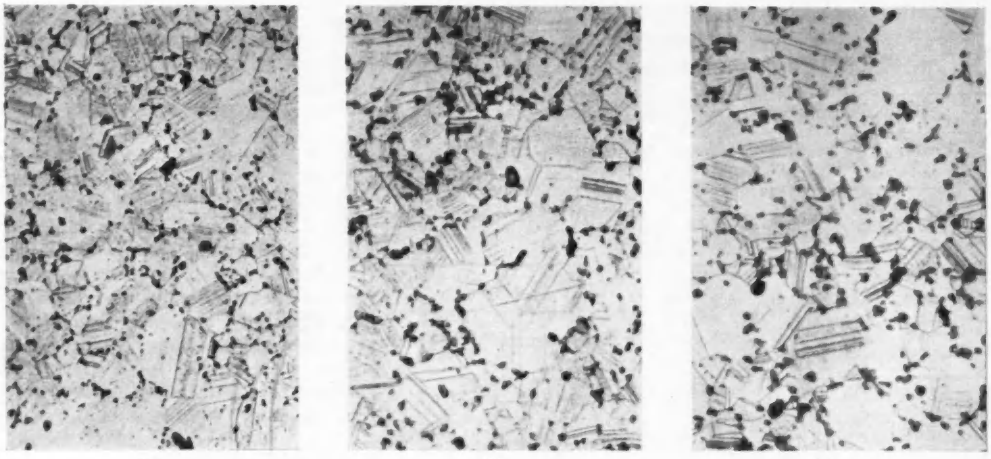
The effect of added carbon on the properties of the sintered alloy is being investigated, and attempts have been made to carburise the alloy. The methods used were: (*a*) the addition of elemental carbon in the form of finely divided graphite, to the mixture of powders before compacting and sintering; (*b*) gaseous carburisation; (*c*) the use of carbides of one or more of the individual constituents of the alloy; (*d*) the use of a "master" alloy powder of Vitallium containing about 5 per cent of carbon; and (*e*) combinations of these.

TABLE 13.

ROOM-TEMPERATURE MECHANICAL PROPERTIES OF SINTERED BASIC ALLOY CONTAINING THORIA.

Thoria Content, per cent	U.T.S. tons/sq. in.	L. of P. tons/sq. in.	Elongation on 0·625 in. per cent
0·3	41·5	31·5	4·0
0·1	52·2	40·2	5·1

The use of elemental carbon resulted in very low density material with marked porosity and with little or no indication of carbide formation. The rate of carburisation in a carburising atmosphere above 1,200 degs. C. tended to be so great that it was difficult to avoid the formation of a heavily carburised surface and consequent



(a) (b) (c)

Fig. 12.—Etched sections of sintered Vitallium alloy, sintered for 8 hours at 1,325 degs. C. in dry, purified hydrogen : density 8·42 g./c.c. (x 180) ; (a) 0·1 per cent thoria ; (b) 0·3 per cent thoria ; (c) 0·5 per cent thoria.

melting. Within the range of 1,150-1,200 degs. C., however, although the rate of carburisation was still high, some degree of control was possible by the interposition of diffusion periods in pure hydrogen between bursts of carburisation (see fig. 13).

Reasonable densities were obtained with tungsten carbide (see fig. 14a), but the total carbon which could be introduced by this method alone was less than 0·5 per cent. The use of the " master " alloy powder of Vitallium containing carbon was encouraging ; a product approaching 98 per cent of the theoretical density was prepared (see fig. 14b).

DISCUSSION.

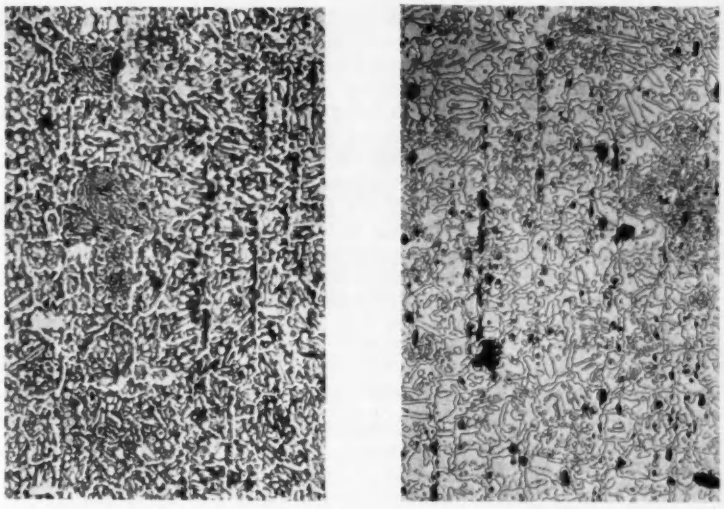
The investigation has shown that with a correct blending of powders having suitable characteristics, and with adequate control over the sintering conditions, it is possible to produce a high-quality product which, in the as-sintered condition, has a density very close to the absolute density of the alloy, in spite of the absence of a liquid phase during sintering. The attainment of such a density in sintered alloys in the absence of a liquid phase is unusual in powder-metallurgy practice. No attempt has been made to investigate the fundamental mechanism of the sintering process, but it is apparent from the work already

TABLE 14.

RESULTS OF N.P.L. CREEP TESTS AT 650 degs. C. and 750 degs. C. ON SINTERED BASIC ALLOY CONTAINING THORIA.

Thoria Content	Stress and Temperature	Time for Specific Creep Strains, hrs.						Time for Fracture, hr.	Elongation, per cent
		0·1%	0·3%	0·5%	1·0%	2·0%	3·0%		
Nil	6 tons/sq. in. at 750 degs. C.	7	38	81	187	330	410	534	4 on 1½ in.*
0·15	Ditto	9	50	108	225	375	—	453	4·25 on 2 in.
0·10	Ditto	10	84	202	444	668	—	738	3 on 2 in.
0·30	Ditto	3	17·5	35	68	127	163	182	5·5 on 2 in.
Nil	12 tons/sq. in. at 650 degs. C.	25	125	224	525	1,080	1,450	1,940	7 on 1½ in.
0·05	Ditto	34	165	392	—	—	—	shut down 700	—
0·30	Ditto	7	44	89	198	362	—	418	2·5 on 2 in.

* Fractured at gauge mark.



(a) (b)

Fig. 13.—Etched sections of sheet hot-rolled from sintered Vitallium alloy and treated in carburising atmosphere (x 200).

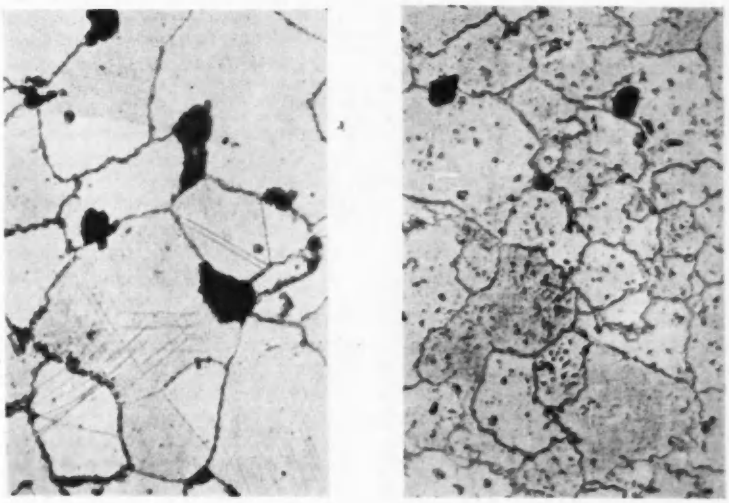
(a) 2 hours at 1,150 degs. C. in dry hydrogen and 5 per cent CH_4;

(b) Treated as (a) and followed by 5 hours' diffusion at 1,150 degs. C. in dry hydrogen.

done that the high-purity hydrogen used as the sintering atmosphere plays an important rôle.

The room-temperature properties of the sintered Vitallium-type alloy compare favourably with those of the material cast from identical constituents and with the published data for cast materials of similar composition containing carbon. The elongation and impact values of the sintered alloy are, in fact, somewhat higher than those of the commercial cast alloys.

While high-temperature fatigue tests are encouraging, the overall strength of the sintered alloy, particularly in creep, is low at temperatures above at least 600 degs. C. This may be associated with the absence of the strengthening intergranular network of carbide found in the commercial cast alloy, or it may be evidence of the weakness of the intergranular bond in sintered material. Extrapolation of Grant's work on the effect of carbon content on high-temperature strength would suggest that the difference in performance between the sintered alloy and the



(a) (b)

Fig. 14.—Carburised Sintered Vitallium alloy.

(a) Carburised by adding tungsten as tungsten carbide in powder mix; carbon content approximately 0·4 per cent (x 200).

(b) Carburized by use of Vitallium—carbon "master" alloy in powder mix; carbon content approximately 1·0 per cent (x 200).

nearest equivalent commercial cast alloy can be accounted for almost completely by the difference in carbon content. It is hoped that work now in progress will supply additional information on this aspect, and will indicate means of strengthening the sintered product at high temperatures.

The phenomenon of ageing exhibited by the sintered alloy on heat-treatment around 800 degs. C. is associated with the transformation from the face-centred cubic structure to the hexagonal close-packed. The lattice parameters determined for the two structures are: face-centred cubic, $a_o = 3{\cdot}5726 \pm 0{\cdot}0005$ Å. and hexagonal close-packed, $a_o = 2{\cdot}5321 \pm 0{\cdot}0003$ Å. $c/a = 1{\cdot}6113$. So far, there is no X-ray evidence to suggest the presence of any precipitation phase as the result of the ageing treatment, but if it is assumed that no precipitation is involved in the transition, and that the compositions of the two phases are identical, then these lattice parameter values lead to different values of density. The calculated mean atomic volume for the face-centred cubic structure is 11·39 cu. Å., and for the hexagonal close-packed structure 11·32 cu. Å.

The X-ray patterns reveal the incompatibility of the two phases by the non-coincidence of the 0002 hexagonal reflection with the 111 face-centred cubic reflection. If the transition were to occur without distortion it is reasonable to expect that the 0002 hexagonal and the 111 face-centred cubic reflections would occur in the same position. The 0002 hexagonal is found to be displaced slightly towards a higher Bragg angle than the 111 face-centred cubic, and the displacement is particularly well revealed in the X-ray photograph of a specimen in which the two phases are present in approximately equal proportions.

Exactly what such differences of density involve is not yet clear, but it seems likely that, at least in the case of partial transition, internal strains must be set up which may account for the changes of tensile properties during ageing.

There has been a general impression that the oxidation resistance of a sintered product is inferior to that of its cast or wrought equivalent. The present work has shown, however, that, provided a high density is obtained, the oxidation resistance of the sintered product can equal that of the cast alloy.

The control over grain size which can be obtained by the sintering process may be an important factor in its favour where the overall performance of an alloy may be determined by consistently controlled grain size. It is proposed to study the effect of the grain size of the sintered alloy on high-temperature creep and fatigue resistance.

ACKNOWLEDGMENTS.

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Radio Frequency Heating in Industry

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The use of radio frequency heating has been extended to many industrial processes during the past few years. The characteristic features of both dielectric heating, for insulating materials, and induction heating, for electrical conductors, are described.

A comparison is made between the rates of energy transfer commonly obtained when using conduction, convection, radiant and R.F. heating.

Several industrial applications of dielectric and induction heating are described and a rough indication is given of the capital expenditure and the running costs involved.

This paper was read by the author at the British Electrical Development Association's Sales Management Conference, held in Caxton Hall, London, May 24th, 1951.

INTRODUCTION.

HEATING, by one or more of several methods, is used at some stage in the production of a wide range of basic materials and manufactured articles. Heat is necessary for melting, annealing, hardening steels, for softening plastics, curing synthetic resin glues, drying paint finishes, and for many other processes. Electrical heating offers advantages for many of these processes and is widely used in industry. For example, in some factories the electrical load for the heat treatment of metals amounts to many hundreds, or even thousands of kilowatts.

Electrical heating methods fall into two separate classes. In one, the heat is transferred from a source at a high temperature to the article to be heated. In the second, the heat is generated in the article itself and the source of energy is not at a high temperature.

The three different ways in which heat is transferred from a high temperature source are by conduction, convection and radiation, or as frequently happens in practice, by a combination of these methods. In high temperature resistance furnaces, for example, although the charge is heated mainly by radiation, the transfer of heat by conduction and convection is appreciable.

Heat may be generated directly in the article to be treated either by conducting a current through it or by inducing a current in it. In the first method, which is used to a limited extent for soldering, heating prior to forging and for some other applications, an alternating current, at a frequency of 50 c/s is passed through the article, or through some part of it. In the second method, alternating currents, mostly of much higher frequencies are used, and contact with the article being heated is unnecessary. This method is known generally as high frequency heating and, in particular, when the frequencies used are between about 100 kc/s and 100 Mc/s, which is in the range also used for radio communications; the method is called radio frequency heating.

Radio frequency heating comprises two distinct methods; eddy-current or induction heating for electrical conductors, and dielectric heating for materials which are normally regarded as electrical insulators. Induction and dielectric heating are not fundamentally new methods, but it is only within the last decade that their use has been extended to cover a wide range of industrial processes.

This paper is primarily concerned with the more recent uses of induction and dielectric heating. The sources of high frequency power are described. The characteristics of each method are considered and briefly compared with those of the more conventional heating methods. Several industrial applications are described, and a general indication is given of the costs involved.

SOURCES OF HIGH FREQUENCY POWER.

Three main types of generator are used for converting power taken from the low frequency supply mains into high frequency power. These are, the spark gap oscillator, the alternator and the valve oscillator. They differ in output frequency, power and in other characteristics. Although this paper deals with the radio frequency valve generators and their uses it is appropriate to mention some features of the other types of generator for comparison purposes.

Spark Gap Oscillators.

This type of generator consists essentially of an H.T. transformer, a spark gap and an oscillatory circuit. Spark gap oscillators, having output powers of up to 35 kW and frequencies in the range of 12 kc/s to about 200 kc/s, have been used for induction heating. The efficiency of these generators is about 50 per cent. Spark gap oscillators are not used as widely as either alternators or valve oscillators.

Alternators.

High frequency alternators have been used for many years and still constitute the largest connected load for induction heating. In the five years immediately preceding the last war the total output of H.F. alternators in the Sheffield area alone increased from 6,000 kW to 16,000 kW.

Alternators differ constructionally in several ways, but all operate at fixed frequencies which are usually within a range 500 c/s to about 15,000 kc/s. The output powers of high frequency alternators used for heating vary from about 50 kW to several hundred kilowatts, the higher powers being usually associated with the lower frequencies. The output voltages are usually between 200 and 1,500. A 400 kW, 1,000 cycle alternator which supplies the power to a steel melting furnace is shown in fig. 1. Alternators are of no use for dielectric heating as the frequencies and voltages are far too low for effective heating.

Valve Oscillators.

This type of generator, although used for heating as long ago as about 1925, has been developed considerably within the last ten years and brought into more general use. The generator consists of an H.T. transformer and a rectifier unit, which supplies a high voltage direct current to one or more triode valves and an oscillatory circuit. Radio valves which are similar, and in some cases identical to those in radio transmitters, are used, and in all but the smallest sets the valves are force-cooled by air or water.

For most valve generators having an output of 1 kW or over, a three-phase supply is required and the power factor of the generator is usually in the region of 0·85 to 0·95. Valve oscillators having maximum output powers of a few hundred watts up to about 200 kW, are available for heating applications.

For induction heating, frequencies between a few hundred kilocycles/second and a few megacycles/second are generally used. The frequencies used for dielectric heating are usually much higher, the range being from about 2 to 100 Mc/s. Here again, as with the alternators, the higher frequencies are usually associated with the lower powers. The radio frequency output voltages may vary from a few hundred to 10 or 12 thousand, depending on the size of the generator and the purpose for which it is required. The efficiency depends to a large extent on the nature of the load, but it is usually in the region of 50 to 60 per cent.

Valve generators are switched on in two stages. First, the valve filaments, fans and other auxiliaries are connected. Under these "stand-by" conditions the power consumption is quite small. Then, after a short delay, the H.T. supply is connected to the oscillator circuit and the full output power is available. Two important characteristics of this type of generator are, first, that the warming up period is brief and second, the demand from the supply mains is large only when the power absorbed by the article being heated is high.

The high D.C. voltages are confined to circuits within the valve generator cabinet and special precautions are taken to prevent the oscillator being switched on when inspection panels are removed and doors opened. Radio-frequency voltages, although not lethal, can produce dangerous burns, and precautions are therefore taken to prevent the operator touching any part of the output circuit. It is also necessary to screen the output circuits electrically to reduce any radiation which might interfere with radio communications. For dielectric heating the output terminals are connected to two metal plates, or electrodes and for induction heating they are connected to a copper coil. Very often a matching circuit is connected between the electrodes or the heating coil and the output terminals of the generator, to ensure maximum power transfer to the load.

For some uses of radio frequency generators a constant energy output is required. For these, energy controllers can be used and small variations in the input voltage to the generator are not very important. For many other applications, however, for which a constant power output is needed, the wide variation in input voltage and frequency can prove troublesome. If satisfactory results are to be obtained in these circumstances it is often necessary either to stabilise the input to the generator or to regulate the output.

It will be apparent that the installation and maintenance of valve generators require special consideration. Even the largest valve generators do not require special foundations, and equipment manufacturers usually arrange for their own engineers to install and check new equipment. Similar arrangements are also made for

the servicing of the equipment. Any minor adjustments required are usually carried out by the Works electrician.

Some factories which use several high frequency heating sets have their own engineer who not only supervises the maintenance of the generators, but designs any new jigs, electrode arrangements and heating coils that are required.

CHARACTERISTICS OF DIELECTRIC HEATING.

When an insulating material, or dielectric is placed between two parallel electrodes, across which a radio frequency voltage is maintained, heat is generated in the material. If the material is homogeneous and of uniform thickness this heating is uniform throughout. The rate of heating depends on the voltage across the dielectric, on the frequency and on the electrical properties of the material itself. More rapid heating is obtained with higher voltages and also with higher frequencies. If the thickness of the material varies, the voltage across different sections of it will not be the same, and because of this variation the heating will not be uniform. Sometimes, however, the uneven heating can be reduced by suitably shaping the electrodes. Different materials, even of the same thickness when placed together between parallel electrodes will not heat at the same rate, because of the difference in their electrical properties.

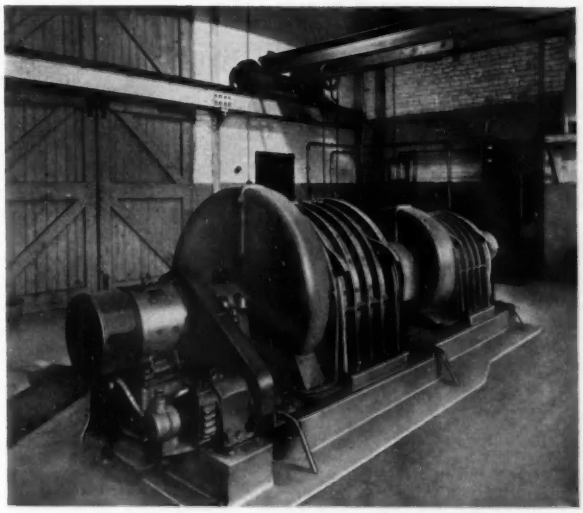

Fig. 1.—A 400 kW, 1,000 cycle alternator supplying power to the induction type steel melting furnace shown in fig. 5.

Very little heat is generated in the electrodes and they remain cool unless heated by the dielectric. Because of the loss of heat from the outer surfaces of the dielectric to the cold electrodes and to the surrounding air, the temperature inside the material is higher than outside. It will be appreciated that this is the opposite of what happens when other methods of heating are used. Dielectric materials such as wood and some plastics can be heated at rates of up to 100 degs. C./minute. A few materials can be heated at much higher rates. Most thermal insulators are suitable for dielectric heating and it is therefore apparent that this method is most effective for the rapid through heating of these materials. The temperature required for processing most dielectric materials are in the range 80 degs. C.-200 degs. C. and rarely are temperatures above 300 degs. C. required.

It is not essential for the electrodes to touch the dielectric and advantage is sometimes taken of this fact in choosing the most suitable heating arrangement. For example, when material is heated on a conveyor, there is invariably an air gap between the material and at least one of the electrodes. The voltage gradient across the material is usually less than 3,000 volts/cm. and the total voltage across the electrodes rarely exceeds 10,000 volts.

There are two factors which limit the extent to which voltages and frequencies can be increased to obtain more rapid heating. When too high a voltage is used there is a breakdown of either the dielectric or the air between the electrodes. If too high a frequency is used when heating large areas, then the voltage across different parts of the electrodes varies and in consequence the heating is no longer uniform.

Advantage is often taken of the fact that two materials, which have different electrical properties, heat up at different rates when placed side by side between the electrodes. For example, when gluing pieces of wood together, synthetic resin glues can be heated more readily than wood and it is therefore possible to cure the glue without heating the wood appreciably.

To sum up, dielectric heating is principally a method of achieving the rapid through heating of thick sections of materials of low thermal conductivity. It is also used for

the selective heating of assemblies of different dielectric materials.

CHARACTERISTICS OF INDUCTION HEATING.

When an electrical conducting material such as steel, brass, or graphite, is placed in a coil carrying a high frequency current, a current is induced in the material and heat is generated in it. The current is greatest at the surface of the body and decreases as the depth below the surface increases. Consequently, in contrast to the uniform heating of dielectrics, the heat is generated in a very thin surface layer of the conducting material and reaches the inside by thermal conduction. The depth of this layer decreases as the frequency is increased. At a frequency of about ½ Mc/s, which is in the range used by many radio frequency induction heating generators, the depth of layer is only a few thousandths of an inch.

The heating effect increases with the magnitude and frequency of the current in the coil and also with the resistivity and permeability of the material being heated. When similar sized samples of steel, brass or copper are placed in a coil the steel heats more than brass, and both heat more than copper.

In the same way as the induced currents flow in a thin surface layer of the material being heated, so the currents in the heating coil and in the oscillator circuit are concentrated near the surface. Because of this skin effect a large surface area is more important than a large cross section in radio frequency current conductors. Foils and tubes are frequently used for radio frequency circuit connections and for heating coils. Because the heating effect in copper is comparatively small it is used for the heating coils and for radio frequency current leads inside the generator. Even so, the heating of the circuit is appreciable, and especially in induction heating generators, where large currents are common, the tubular heating coils are usually water cooled. Silver plating is sometimes used to reduce the heating losses in coils and circuit connections.

Most valve generators used for induction heating operate at frequencies from about 400 kc/s to 5 Mc/s. The frequency is usually chosen to meet generator design requirements rather than to obtain specific heating effects. Different heating effects are usually obtained by altering the rate and time of heating rather than by changing the frequency.

The rate at which energy can be transferred to the surface of an article by induction heating may be as high as 20 kW/sq. in. Heating times vary from a fraction of a second to several seconds, or even minutes, depending on the power density used and the temperature required. Surface temperatures of up to 900 degs. C. can be reached in a second. The higher power densities and short heating times are used when it is necessary to heat the surface of a body to a much higher temperature than the inside, or in other words, when a steep temperature gradient is required. When low power densities are used thermal conduction to the inside of the body plays a much more important part and even thick pieces of metal are effectively through heated. Under these conditions heating times are longer.

Heating coils can be made of many different sizes and shapes to suit various components. When it is necessary to heat only a small area

Fig. 2.—2 kW. dielectric heating set for preheating thermo-setting plastic material prior to moulding.

of a particular component, rapid local heating can be obtained by a suitable arrangement of the heating coil.

To sum up, induction heating is a method of rapidly heating electrically conducting materials. Pronounced surface heating effects, or through heating can be obtained, and the heat can also be localised.

COMPARISON OF HEATING METHODS.

Before describing some of the production uses of induction and dielectric heating it is appropriate that these methods should be related to the more conventional forms of electric heating.

CONDUCTION.

Electrically heated strips, rods, plattens (hot plates) and rollers are frequently used for heating plane surfaces. Good contact with the surface to be heated is essential and the rate of transfer depends on the thermal properties of the material heated, being much less for wood than metals. The maximum power transfer to metals is of the order of 10 kW/sq. ft. For poor thermal conductors such as wood, the temperature of the heater must be kept to a low value to avoid damaging the surface of the material by overheating, and the maximum rate of transfer is only about 250 watts per sq. ft.

CONVECTION.

The rate of transfer of heat by natural convection to both conductors and non-conductors is low and heating times are long. For an air temperature of 250 degs. C. the initial rate of energy transfer to the surface of an article is less than 200 watts/sq. ft.

If the velocity of the air is increased, the rate of energy transfer is substantially improved. For example, when the velocity of air at 250 degs. C. is increased to 20 ft./sec., the initial rate of energy transfer is more than trebled.

As the article warms up, the difference between its temperature and that of the air diminishes and the rate of heating falls off. Convection ovens are mostly used for temperatures below 300 degs. C. and heating times are often an hour or more.

RADIATION.

Radiant heating is equally applicable to conductors and non-conductors. With most materials the energy is absorbed very near the surface and the heat reaches the inside of the material by conduction. The intensities used in radiant heating depend upon the source employed. For lamps, the maximum power density is about 1 kW/sq. ft. and the maximum temperature obtained is about 300 degs. C. When sheathed wire elements or open resistance wire elements are used, much higher power densities can be obtained, and higher temperatures reached. Heating times for many processes, such as paint drying and softening plastic sheets, are of the order of a few minutes.

DIELECTRIC HEATING.

With this method, which is only applicable to non-conductors such as wood, rubber and plastics, heating rates are many times greater than those achieved by any other method. Rates of energy transfer equivalent to surface densities of up to 10 kW/sq. ft. can be obtained. Dielectric heating is rarely used for temperatures above 300 degs. C. and heating times varying from a few seconds to minutes are usual.

INDUCTION HEATING.

This method is only applicable to electrical conducting materials. The maximum power densities employed are roughly 1,000 times as great as those commonly used for radiant heating. For many applications, heating times are of the order of a few seconds only. When required, temperatures of at least 2,500 degs. C. can be obtained.

INDUSTRIAL APPLICATIONS OF DIELECTRIC HEATING.

The earliest use of valve oscillators for dielectric heating was for medical treatment, or diathermy as it is called. During the war, generators having output powers of about 1 kW were used to speed up the moulding of plastics, and larger sets were used for making shaped wooden panels for aircraft. Since then, the use of dielectric heating has spread to other industries.

PLASTICS.

It is probable that more dielectric sets are used for preheating plastic material than are used for any other single application. For some mouldings, the thermosetting plastic material is used in powder form and for others, it is pressed into pellets of uniform size and weight. If the material, in either form, is not preheated before being placed in the mould, a period of several minutes must be allowed for the heat from the mould to soften the plastic, before the press can be completely closed. The press time required for moulding thermosetting plastic material is

considerably reduced if it is through heated before being put into the mould.

Dielectric heating sets with an oven containing two flat plate electrodes have been specially built for preheating plastic powders and pellets. The charge of plastic material, which may weigh from a few ounces to several pounds, is placed on the lower electrode and the rate of heating can be adjusted to suit the press cycle. When the oven lid, or door, is closed, the electrodes are completely screened, and only then can the R.F. power be switched on.

The heating time is controlled by an electric process timer, and, as in many other high frequency heating applications, the uniformity of heat treatment is based on the supply of energy at a controlled rate for an accurately measured time. The electrical loading of the generator is indicated on a meter and no skill is required in operating this type of equipment.

Plastic preheating sets usually have a maximum power output of 1 or 2 kW and operate at frequencies of about 15 or 20 Mc/s. The weight of the plastic material that can be heated to the temperature required for moulding in a minute is about $\frac{3}{4}$ lb./kW.

For many mouldings, thermosetting plastic materials can be preheated quite satisfactorily in small radiant heating ovens, but for maximum flow, for thick sections, or where there are delicate inserts, dielectric heating must be used. In addition to reducing the time required in the press, better quality mouldings are obtained, and the wear of the dies is less. Fig. 2 shows a dielectric preheating set in use in a moulding shop.

Other plastic heating applications include the seam-welding of thermoplastic sheets, to make such articles as garments and containers. Different techniques are used for making the seams depending on their size and shape. In one, the thermoplastic sheets are placed between two narrow metal strips, which form the electrodes. The strips are spring-loaded and ensure that the plastic sheets are pushed into intimate contact when they have softened. Long seams are made by successively heating parts of the material between the short strip electrodes. Shaped seams are sometimes made by a single heating between suitably shaped strips. Another technique involves the use of circular electrodes instead of strips. Pieces of materials can be spot-welded together, or alternatively, continuous seams can be made by allowing the welds to overlap. Seam-welding machines have been built which enable continuous seams to be made by passing the thermoplastic sheets between rollers which are connected to the output terminals of an R.F. generator. These machines are similar in appearance to sewing machines and are used in a similar way. Radio frequency generators of less than 1 kW output, operating at frequencies up to 60 Mc/s, are used for this application, and welding speeds up 10 ft./minute can be obtained.

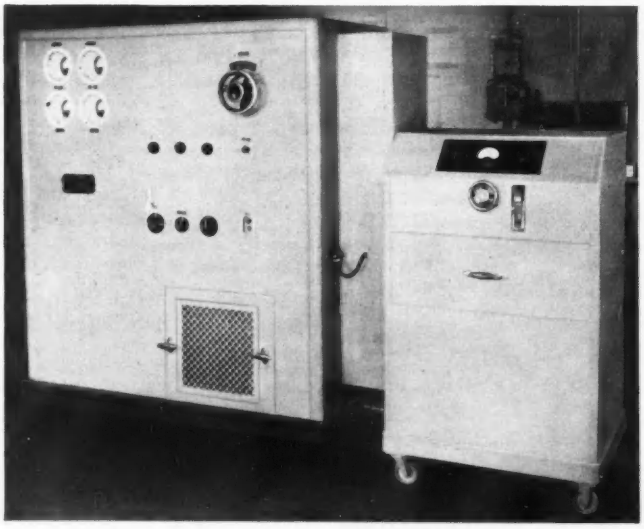

Fig. 3.—5 kW dielectric set for preheating blocks of rubber prior to moulding.

RUBBER.

The dielectric heating of rubber prior to moulding also enables a greatly increased output to be obtained from each press. Dielectric heating sets having greater outputs than those used for preheating plastics are used, and the oven is usually a separate unit which is fixed alongside the generator. In a typical equipment, which is illustrated in fig. 3, three blocks of rubber about 2 ins. thick and each weighing 4 lbs. are preheated to about 80 degs. C. in five minutes. The moulding time in the press is only one third of that required when the rubber is not preheated. Heating rates considerably

less than the maximum are chosen for preheating loaded rubber stock. By using slower heating rates it is possible to avoid local overheating, which sometimes occurs, even in uniform sections, because of the uneven dispersion of carbon black in the material. Even so, as this example shows, the increase in output is considerable. Rubber to be vulcanised and bonded to metal can sometimes be successfully preheated by this method.

WOOD.

Dielectric heating is frequently used in the manufacture of flat and curved section plywood and in furniture making, for accelerating the curing of synthetic resin glues.

When making flat plywood in thicknesses greater than about $\frac{3}{4}$ in., dielectric heating can be used to reduce the setting time required in the press, and so increase output. The glued veneers are placed between parallel electrodes in a press, and with this arrangement the glue does not heat more than the wood. Precautions are taken to prevent excessive cooling of the veneers by the platens of the press. In a typical installation using dielectric heating a 12 in. thick stack of boards measuring 48 ins. by 40 ins. is heated to a temperature of about 95 degs. C. to cure the glue, in about 20 minutes, and it is of little consequence whether the individual boards are $\frac{1}{2}$ in. or 6 in. thick. For blocks thicker than 1 in. the saving in time is considerable when dielectric heating is used. A large installation for making flat plywood is illustrated in fig. 4.

In a similar way curved section plywood can readily be made, using simple wooden moulds faced with thin metal sheets to act as the electrodes. To quote one example, the glue in a curved section of plywood measuring 7 ft. 6 ins. by 2 ft. 2 ins. by $3\frac{3}{8}$ ins., which is used to make ribs for railway carriage sides, is cured by dielectric heating in five minutes. Only five units of electricity are needed for each board. The more conventional methods of making curved sections are still widely used, but where a large output is required, dielectric heating is frequently employed.

Setting glued joints in cabinet and furniture assemblies is now a well-established application of dielectric heating. By the use of dielectric heating it is possible to reduce setting times from several hours to a few minutes, or even seconds, and as a result there is a substantial saving in the number of jigs and clamps required. Dielectric heaters having powers of 1 to 5 kW are generally used, and the jig and electrode assembly is accommodated in a screened enclosure alongside the generator. The electrode arrangements depend on the size and position of the joints, but the heating is, so far as possible, confined to the joint. The electrodes, which are usually copper strips or tubes, can frequently be placed so that the glue heats more rapidly than the wood and setting times of less than a minute are obtained.

Fig. 4.—25 kW dielectric heating installation for making flat plywood. The matching unit located between the generator and the press ensures that the generator is always loaded most efficiently.

One further application of dielectric heating which is of interest is the gluing of strips of wood, edge to edge, to make large panels of blockboard. Machines, called "edge gluers" for making panels in this way are reported to be used extensively in America. The machine consists of a dielectric heating set and a press in which the strips of wood are held under pressure while the glue is set. Here again, the electrodes are arranged so that the glue heats much more than the wood and setting times of 20 seconds to a few minutes, depending on the size of the panel, are claimed. Dielectric heating is not extensively used for making blockboard in this country.

Fig. 5.—Pouring steel from a 10 cwt. induction furnace at a Midland foundry.

DRYING.

Materials containing water are easily heated by the dielectric method. There may be occasions when dielectric heating can be used with advantage for drying special materials, but the method is too expensive for general use. Textiles and ceramics have been successfully dried on an experimental scale, but this method is not used in production.

MISCELLANEOUS APPLICATIONS

The twist setting of rayon, and the drying of foundry cores are two other processes to which dielectric heating can be applied, but so far the method is not widely used on a production scale.

Many other uses of dielectric heating have been proved to be technically feasible, but have not been developed further because of the high cost. For example, loaves can be baked in five minutes in a dielectric oven, but an analysis of the cost of this process leaves little doubt that the use of resistance ovens will continue.

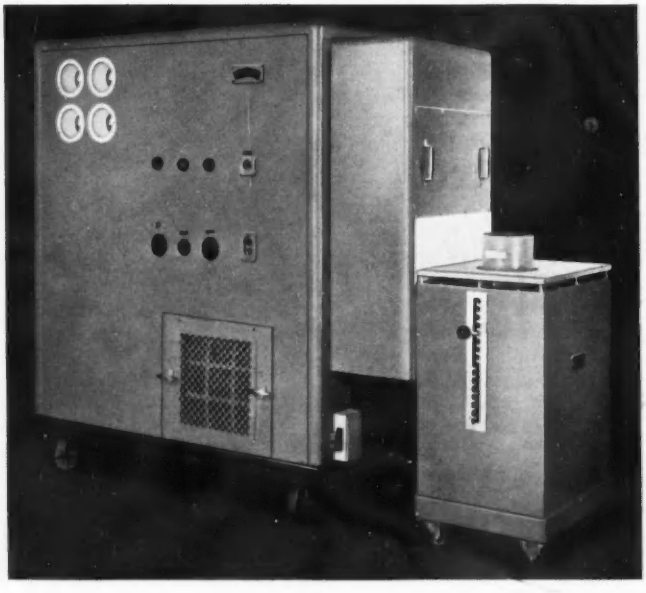

Fig. 6.—5 kW radio frequency induction furnace for the rapid melting of small quantities of metals.

NDUSTRIAL APPLICATIONS OF INDUCTION HEATING.

For at least 25 years, valve generators have been used for heating the electrodes of radio valves in the final stages of manufacture, but within the last ten years their use has been extended to many other processes.

suitable for quantity production. By suitable arrangement of the coils, the heating effect is confined to the immediate neighbourhood of the joint, thus ensuring the maximum economy in the energy and time required. Localised heating also tends to reduce the distortion which is sometimes troublesome when other methods of

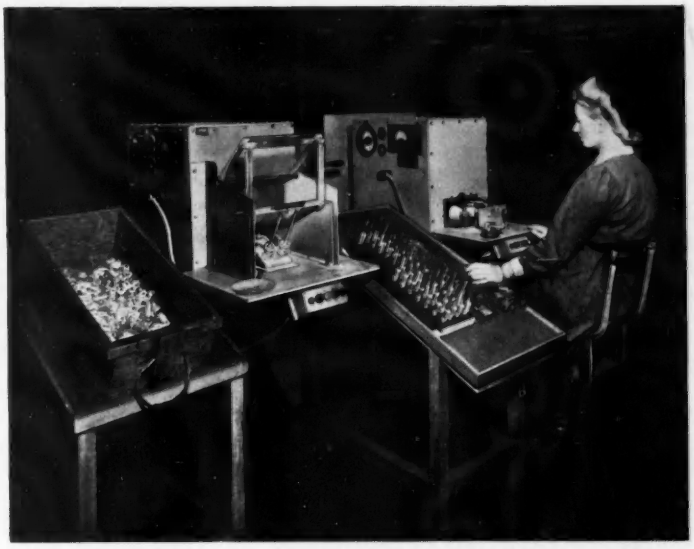

Fig. 7.—1 kW radio frequency induction heaters used for soldering and brazing small assemblies.

Melting.

The melting of both ferrous and non-ferrous metals in quantities up to several tons was one of the early applications of high frequency alternators and remains one of the most important. A 10 cwt. induction steel melting furnace is shown in fig. 5. Valve generators are now used for melting small quantities of metals in the temperature range 1,000 degs. C. to 2,500 degs. C. Induction heating is specially suitable for vacuum and controlled atmosphere furnaces.

In one typical vacuum installation copper billets are melted and cast in vacuum to make anodes for X-ray tubes. The castings, varying in weight up to 3 lbs. are melted in 14 to 20 minutes.

An induction furnace, in which a charge of about 2 lbs. of steel or 3 lbs. of copper can be melted in about 10 minutes, is illustrated in fig. 6.

Soldering and Brazing.

Induction heating is used for soldering and brazing a wide variety of parts and is particularly heating are used. By using controlled amounts of solder or brazing material and by timing the heating period, high standards of uniformity can be maintained. Many parts can be satisfactorily heated on a continuously moving conveyor, while others can more easily be treated in a fixed position. Whichever method is adopted skilled operators are unnecessary. Some parts can be soldered better by induction heating than by any other method and some specifications call for treatment by this method.

A few examples of induction soldering which are in production use will illustrate these points. A 1 kW induction heating set solders the tops on condenser cans at the rate of 700 an hour. This output is achieved by one girl, who places a ring of solder over the joint and puts the condensers on a conveyor. The number of rejects is reduced to negligible proportions.

The soft soldering of a hub and tube assembly, which was particularly difficult by ordinary methods, is speeded up by the use of induction heating. The quality of the product is greatly improved, and the number of rejects is

considerably reduced. The output of these parts is now four times the previous figure. This increased output is achieved by one girl who assembles the parts, fluxes the joint, puts the shim of solder in position and mounts the assembly on a simple fixture inside the heating coil. The economy effected by using induction heating is substantial. The installation for soldering these parts is shown in fig. 7.

The brazing of tungsten carbide tips to various shapes and sizes of cutting tools is carried out by induction heating at the rate of one every 20 or 30 seconds. The heating is much more localised than with furnace treatment, there is no scaling and little skill is required for this operation. An installation using R.F. heating for brazing tips to cutting tools is shown in fig. 8. A further R.F. installation for brazing gas water-heater parts is seen in fig. 9.

Many other examples could be quoted where substantial economies have resulted from increased output per operator, a reduction in the number of rejects and the elimination of cleaning and machining operations. In many cases the capital cost of the equipment used has been saved in a few months.

Fig. 9.—Brazing gas water-heater components with a 5 kW R.F. generator installation.

Fig. 8.—A 5 kW R.F. generator being used for brazing tungsten carbide tips to cutting tools.

Hardening of Steels.

When steels are heated at surface densities of 4 to 20 kW/sq. in. a shallow surface layer can be raised above hardening temperature before the core becomes very hot. If the steel is then quenched, a hard surface case is produced.

High-frequency alternators were used for the surface hardening of steel in America about 1935 and similar equipment is still being used for many surface hardening applications. At the higher frequencies obtained with valve generators the heating takes place in a thinner surface layer than when the alternator frequencies are used. It is therefore possible to produce thinner hardened cases when using valve generators.

Induction hardening, using valve generators, can be applied to many

Fig. 10.—1 kW R.F. generator being used for the local hardening of a lever cam.

different shapes and sizes of component, such as ball pins, rocker pads, shafts, gears, tappets and camshafts. Two methods of hardening are commonly used. In one, the whole area to be hardened is heated at once and then quenched. Because of the high-power densities required to get the correct heating effect, only a limited area can be treated in this way. To overcome this limitation, larger areas are processed by a scanning method.

Many advantages can be obtained by induction hardening. The equipment can be put in the production line and the handling of components reduced to a minimum. Because of the short heating times there is little or no scaling and high rates of production can be obtained with unskilled labour. Heating can often be localised, and distortion reduced to a minimum. Working conditions are also improved.

Two R.F. installations for the local hardening of small steel components are shown in figs. 10 and 11.

Many special machines have been developed for handling different components to ensure that maximum output rates are maintained. For example, several different sizes of rocker pads can be hardened on an automatic machine at the rate of 350-700 an hour. After hand-loading, the heating, quenching and unloading are carried out automatically. Case depths of about $\frac{1}{16}$ in. are obtained. A machine for hardening rocker pads is shown in fig. 12.

Similarly, machines are used for the surface hardening of steel bars. The bars are passed through a short circular coil and heated progressively along their length, at speeds of up to 100 ins. a minute. Case depths of ·030 in. to ·050 in. are commonly obtained by using valve generators, but there is no very definite upper limit. Different case depths are obtained by adjusting the power density and the heating time (or the scanning speed), and not by adjusting the frequency. By using lower power densities than those needed for surface hardening, much smaller temperature gradients are obtained and through hardening can be achieved. Some components have been through hardened at frequencies as high as 10 Mc/s.

The design of the heating coils required for surface hardening is important and cannot always be satisfactorily carried out by the user.

Annealing and Tempering.

Induction heating can be used with advantage for tempering hardened surfaces and for annealing tubes and pressings. The method is most

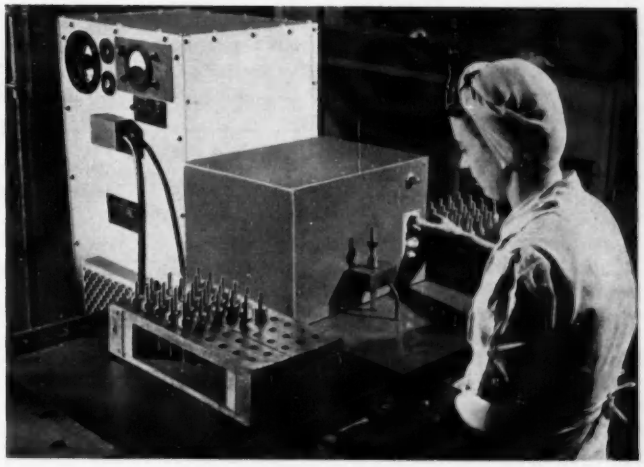

Fig. 11.—Local hardening of diesel engine injector parts with a 1 kW R.F. generator equipment.

useful when large numbers of parts have to be treated and when localised heating only is required.

ECONOMICS.

It is not possible to give more than a general indication of the costs involved in carrying out many of the processes described in this article, but the figures given will serve as a guide. The capital cost of valve generators is about £200 to £350 per kW output for sizes between 1 and 4 kW, and £100-£200 per kW output for sizes between 5 and 30 kW. The cost per kW is less for the higher powers, and the induction sets are more expensive than the dielectric heating sets.

In estimating the running costs, the maximum demand from the supply mains should be assumed to be about double the maximum output power of the generators. Both rectifier and oscillator valves need periodic replacement and their cost should be added to the running costs. Prices of valves vary according to the size and type, and their life which depends on the conditions of use, is usually in the region of 2,000-5,000 hours. On the basis of a valve life of 3,000 hours, the valve replacement cost for a particular 5 kW generator amounts to about 8*d*. an hour. An approximate allowance for valve replacements could be made by adding one penny per unit to the cost of the power supplied to the generator.

In considering any new industrial use of high frequency heating it is advisable to investigate the economics of the process first, and the technical probelms second. The power required for many processes can be assessed from thermal considerations and an estimate can then be made of the capital cost and running costs involved. If this assessment cannot easily be made by the user, manufacturers of radio-frequency heating equipment should be asked to give assistance, and advise on the cost and on the technical possibilities.

CONCLUSION.

Radio frequency heating has become firmly established as an industrial heating method. By greatly increasing the output of each operator, by maintaining a uniformly high quality and reducing the number of rejects, by reducing the skill required, R.F. heating is making a valuable contribution to increasing productivity.

Much more could be done by extending the use of R.F. heating for soldering, brazing, hardening steels, for setting glues in wood assemblies and for treating rubber.

Other industrial applications of R.F. heating will undoubtedly arise, but the method should not be applied with more enthusiasm than wisdom and the economies of any new application should be considered carefully.

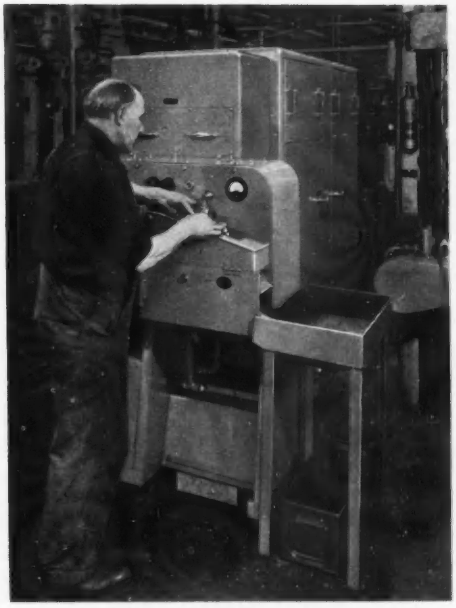

Fig. 12.—Radio frequency induction heating equipment for surface hardening rocker pads at rates of up to 700 an hour.

Isotope Electric Discharge Lamps as Spectral Sources for the Exact Measurement of Length

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Special types of electric discharge lamp producing the line spectra of various elements, have been used for many years in the measurement of short distances to a high degree of accuracy by optical techniques. The development of a lamp containing the single mercury —198 isotope has both simplified these measurements and extended their range of application. Furthermore, the possibility of establishing the wavelength of the green spectral line of $^{198}_{80}$Hg *as a standard of length is receiving international consideration.*

INTRODUCTION.

THE magnitude of any physical quantity is measured as its ratio to a unit quantity of the same kind, and it is therefore necessary to establish the fundamental units before practical systems of exact measurement can be built up. In the C.G.S. (centimetre—gramme—second) system of units the centimetre, gramme and second are chosen as fundamental units, and the units of all other physical quantities are derived from them. The standards of the system are chosen to be permanent, reproducible and, where possible, of a convenient magnitude. This last condition has not been easily attainable in the case of the unit of length.

The first metric length standard was legalised by the French Republic in 1795 and consisted of a bar of platinum which was intended to be one ten-millionth of the earth's quadrant, through Paris, from pole to equator. Later determinations of the quadrant disclosed slight errors, but the original standard bar was defined as the Standard Metre and platinum-iridium alloy copies of it were made in 1889, one being retained in Paris as the International Prototype Metre, the remainder being distributed to various other countries as National Prototype Metres.

While these bars established legally accepted standards of length, they did little to assist the metrologist in measuring small distances to a high degree of accuracy. However, at the same time as the Prototype Metres were prepared, Michelson and Morley[1], in a paper "On the feasibility of establishing a light wave as the ultimate standard of length", described a method for measuring the metre in terms of the wavelength of lines in the emission spectra of various elements, using a wave interference method. As the wavelengths of light waves are very small, ranging from approximately $7{\cdot}5 \times 10^{-5}$ cm. to $3{\cdot}5 \times 10^{-5}$ cm. and are fundamental constants under specified conditions, they are ideal for use in high precision measurement. The red line in the spectrum of cadmium has been selected, from practical considerations, as the standard spectral line and several observers have determined its wavelength directly in terms of the International Prototype Metre. A value of 6438·4696 Å (1 Ångstrom $= 10^{-10}$ m.) has been internationally accepted for the wavelength of this line, under carefully specified conditions both as regards the source of radiation and the ambient medium.

Basically, the method of interferometry referred to above, consists of splitting the light beam from a monochromatic source into two components, which, after traversing different distances, are recombined to give a beam containing two wave trains which are out of phase. Regions of minimum intensity are therefore produced when the phase difference is $(2n + 1)\pi$ and regions of maximum intensity when it is $2n\pi$, the integer n being called the order of interference. By a suitably designed optical system, a symmetrical pattern of alternating bright and dark fringes, usually in the form of parallel lines or concentric circles, can be produced in a given plane. Further, the order of interference can be computed from measurements of the fringe spacing and the retardation calculated in terms of the wavelength of the interfering radiation.[2] A travelling microscope

is used to measure the interference pattern to a sufficiently high degree of accuracy, so that a system of narrow fringes having a high order of definition is essential.

SPECTRAL SOURCES FOR LENGTH MEASUREMENT.

Much of the early work on optical measuring techniques was undertaken with very simple types of light source, the most familiar being a Bunsen burner flame containing a small quantity of volatile metallic salt. Sources of this type have severe limitations both as regards luminosity and stability of light output, disadvantages which quickly led to a recognition of the electric discharge through a metal vapour as a welcome practical alternative. Early forms of mercury and cadmium vapour lamps were used in this way. Increasing need for dependable light sources of this type arose with the development of the use of interferometric methods in various industrial fields.

A wide range of special discharge lamps, designed to produce the line spectra of the rare gases and various metal vapours, has been designed and supplied over the past twenty years by the G.E.C. Research Laboratories and the Osram-G.E.C. Lamp Works.[3] Owing to their high luminosity and stability over extended periods of operation, these sources have proved to be very valuable tools for the optical research worker. Any spectral line from such a source is, however, not composed of a single monochromatic radiation, but spreads with variable amplitude over a small frequency band. This deviation from strict monochromaticity, which varies for different spectral lines, detracts from the definition of the interference patterns produced. Further, the deterioration in definition increases with the order of interference and an upper limit is therefore imposed on the length which can be measured directly. Knowledge of this complex line structure dates back to 1892, when Michelson[4] reported that many spectral lines, including those of mercury, were of a complex nature and this discovery disqualified the use of mercury radiation for precision measurements for over fifty years.

ATOMIC STRUCTURE AND SPECTRAL PURITY.

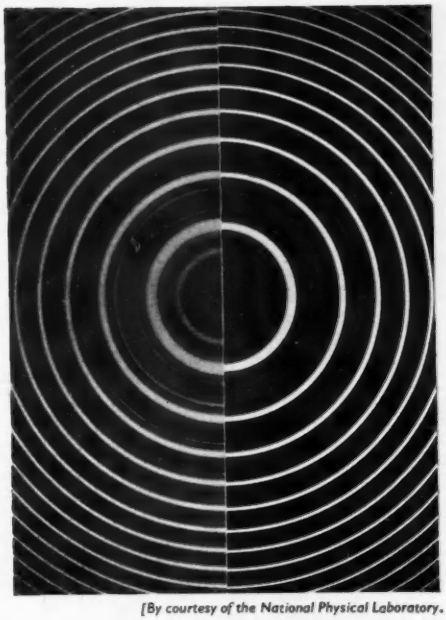
The great advances made in sub-atomic physics during the past fifty years have furnished an explanation for the complex nature of spectral lines in terms of atomic structure. In the case of mercury, for example, the mass spectrograph has shown that the naturally occurring element is a mixture of seven isotopes, of mass numbers 196, 198, 199, 200, 201, 202, 204, which are present in the proportions shown in Table 1 to give a nett atomic weight of 200·61.[5] The theory of quantum mechanics has shown that each of these isotopes emits radiation of frequencies which are dependent upon its mass and, although the differences in wavelength are extremely small, the interferometer has resolved the complex lines so that they can be quantitatively explained[6] as resulting partly from these isotope shifts and, partly from hyperfine structure due to the nuclear spins of the 199 and 201 isotopes. The hyperfine structure due to the spin of the atomic nucleus is exhibited by all odd mass atoms and is caused by a finite resultant rotational velocity of the nucleus. Isotopes of even mass number, however, have a zero resultant spin and their spectral lines are consequently free from this structure. For the past twenty years it has therefore been recognised that single sharp spectral lines could be obtained by exciting any even mass isotope, provided that such an isotope could be produced in sufficient quantities and with the necessary high degree of purity.

TABLE 1.
ISOTOPES OF MERCURY.

Mass Number	Relative Abundance
196	0·15
198	10·1
199	17·0
200	23·3
201	13·2
202	29·6
204	6·7

PREPARATION OF MERCURY ISOTOPES.

The practical realisation of mono-isotopic sources has been brought about as a direct result of the vast wartime projects for producing isotopes synthetically, or separating them electromagnetically. Powerful neutron sources operating in this country at the Atomic Energy Research Establishment, Harwell, enable gold to be transmuted to the $^{198}_{80}$Hg isotope, and material made available in this way has been used at the G.E.C. Research Laboratories to produce new types of electric discharge lamp for use where the utmost sharpness of spectral lines is required. When pure gold, a mono-isotopic element, of mass number 197, is exposed to neutron bombardment, slow speed neutrons may attach themselves to the nuclei of gold atoms, to form the highly radioactive gold isotope $^{198}_{79}$Au, which decays by β-emission to



[By courtesy of the National Physical Laboratory.

Fig. 1.—Composite Fabry-Perot interferogram in natural mercury and $^{198}_{80}Hg$ green radiations (Retardation 8·5 mm.). Left-hand section shows complex structure due to the various isotopes of natural mercury.

become the stable $^{198}_{80}Hg$ isotope; symbolically:

$$^{197}_{79}Au^0 + 1n^0 \longrightarrow {}^{198}_{79}Au^0 \longrightarrow {}^{198}_{80}Hg^0 + 1\beta^{-1}.$$

The samples of pure gold which are irradiated are in the form of foil 0·1 mm. thick and weigh approximately 10 grammes. These are exposed to neutron bombardment until a calculated 0·1 or 1·0 mg. of $^{198}_{80}Hg$ has been formed, the quantity depending upon the type of lamp for which it is to be used. This small quantity of $^{198}_{80}Hg$ is present as a volume distribution throughout the gold and is distilled off by prolonged heating at a high temperature *in vacuo*. If a concentration of $^{198}_{80}Hg$ higher than 1 : 10,000 is desired, either the neutron flux density or the irradiation time must be increased. The former course can have unfortunate consequences, since some of the $^{198}_{79}Au$ nuclei may take up a second neutron to form $^{199}_{79}Au$, which decays to form $^{199}_{80}Hg$ and, if an appreciable quantity of this second isotope is present, the advantages of the mono-isotopic source are partially nullified.

American workers[7] have described an electromagnetic method for separating mercury isotopes, essentially similar to that used for separating uranium isotopes. By this method they have enriched $^{202}_{80}Hg$ to 98 per cent and $^{204}_{80}Hg$ to greater than 92 per cent. It is not yet known whether these electromagnetically separated isotopes will be prepared in sufficient quantities or with the necessary purity to be of practical use in discharge lamps.

WIDTH OF SPECTRAL LINES OF A SINGLE ISOTOPE.

The great improvement in the clarity of the interference pattern which results when the single $^{198}_{80}Hg$ isotope is excited instead of natural mercury, is clearly demonstrated in the composite interferogram shown in fig. 1. This was produced in green 5,461 Å radiation over a retardation of 8·5 mm. using a Fabry-Perot interferometer. The different components due to the seven mercury isotopes are discernible in the left-hand half of the circular fringe pattern, whereas the right-hand half is composed of single sharp-edged narrow bands typical of the $^{198}_{80}Hg$ isotope.

Before describing the construction of two types of $^{198}_{80}Hg$ discharge lamps, brief mention will be made of several factors which control the width of the simple spectral lines emitted by an even mass isotope. Strict monochromaticity is impossible, even under ideal conditions, since all atoms emit damped vibrations when excited and this gives rise to a finite line width known as the "radiation width". In order to approximate to this ultimate condition, careful attention has to be paid to three other factors which cause line broadening. The first of these is the Doppler effect, which depends upon the velocity of the atom at the instant of emission and is proportional to $\sqrt{\frac{T}{M}}$ where M is the mass of the emitting atom and T its absolute temperature. The line width also increases with the gas pressure in the lamp, the magnitude of the broadening being proportional to the pressure for any particular gas. It is of interest to note that the pressure broadening is asymmetrical and leads to a shift in the central frequency of the spectral line. The last effect, evident in the

green line of mercury, is self-absorption and reversal. As its name implies, this is caused by the absorption of radiation by unexcited atoms of the same kind and is proportional to the square root of the number of such atoms in the line of sight. Incipient self-absorption is evident as line broadening and, as the density, or length, of the absorbing column progressively increases, self-reversal is set up and spurious structure is observed in the spectral line.

COLD CATHODE $^{198}_{80}$Hg LAMPS.

By the nature of the method of preparation of the $^{198}_{80}$Hg isotope, the quantities available are very limited, and the cost is high. The problem has therefore been to develop a source containing only 0·1 mg. of the isotope which would be suitable for all normal optical applications and which could be supplied at an economical price. The most satisfactory form of cold cathode discharge lamp meeting these requirements is shown in fig. 2. The lamp electrodes are large hollow molybdenum cylinders which reduce cathodic sputtering to a minimum and thus limit the rate of "clean-up" of the $^{198}_{80}$Hg as much as possible. The positive column, which is 5 mm. in diameter, is cooled by passing water through a coaxial jacket. The small diameter of the positive column and the water cooling combine to eliminate self-reversal in the green spectral line and to reduce Doppler line broadening to a minimum. Various pressures of neon and argon have been investigated as the carrier gas, and argon at a pressure of 10 mm. of mercury has been standardised. Argon was selected since its spectrum is excited less readily than neon when mixed with mercury vapour, and a pressure of 10 mm. was found to be essential to ensure a satisfactory lamp life. It is interesting to note that the wavelengths of the spectral lines of mercury increase by an average of 0·0001 Å per millimetre of mercury increase in gas pressure, whether it is neon or argon. This value and all other interferometric data quoted here are based on measurements made by the Metrology Division of the National Physical Laboratory, who have collaborated closely in the development of these $^{198}_{80}$Hg lamps.

The cold cathode lamps are suitable for operation from any A.C. supply of 600 volts or over at currents up to 25 milliamp. This maximum operating current is a compromise between a sufficiently high luminosity and an economical lamp life. The actual life at a current of 25 milliamp. is approximately 250 hours and it falls off steeply at currents in excess of this value. Lamp failure is usually due to the "clean-up" of the $^{198}_{80}$Hg by adsorption on the walls of the lamp and its trapping by sputtered electrode material. However, by a suitable heat treatment, a considerable percentage of the $^{198}_{80}$Hg can be released in a lamp which has failed by "clean-up", giving a further period of useful operation.

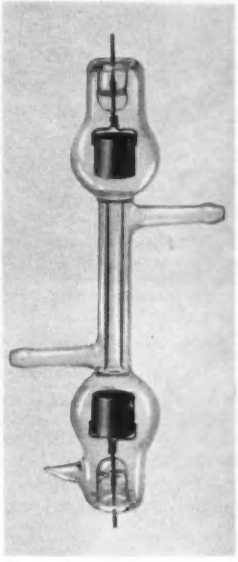
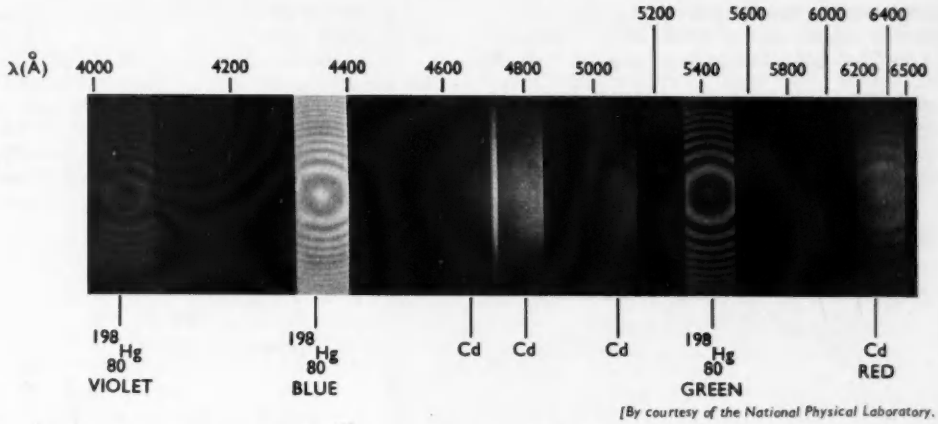


Fig. 2.—Water cooled cold cathode $^{198}_{80}$Hg discharge lamp.

The water-cooled cold cathode lamp is proving a satisfactory source for special applications in spectroscopy and interferometry. The yellow, green and blue lines are suitable for length measurements by visual interferometry, particularly in measurements of reference end standards or block gauges. These gauges, which are used to control linear dimensions in precision engineering workshops, are well adapted to interferometric measurement because of the optical perfection of their surfaces. Furthermore, owing to the strong molecular cohesional forces developed when two polished flat steel surfaces are "wrung" together, the gauge may be placed on a polished flat plate and interference produced in the wave trains reflected from this plate and



[By courtesy of the National Physical Laboratory.

Fig. 3.—Fabry-Perot interferograms for $^{198}_{80}$Hg and cadmium radiations for a retardation of 12·5 cm. These patterns clearly demonstrate the superiority of mono-isotopic radiations for interferometric measurements over large path differences.

the upper end of the gauge. By this method gauges up to 10 cm. in length can be measured to an accuracy of $\pm$ 0·025 microns with a normal interferometer of the Fabry-Perot type and, the range may be extended to 20 cm., when a special Kösters Gauge Interferometer is used. This upper limit, which corresponds to an order of interference of approximately 350,000 for green $^{198}_{80}$Hg radiation, is imposed by the relatively low luminosity of the source and not by the loss in definition of the interference pattern. The upper limit is considerably increased when photographs of the fringes are taken, fig. 3 showing interferograms of $^{198}_{80}$Hg and cadmium radiations for a retardation of 12·5 cm. These patterns were obtained by focusing the light emerging from a Fabry-Perot interferometer on to the slit of a prism spectrograph adjusted for photography of the whole visible spectrum.

TABLE 2.

WAVELENGTHS of $^{198}_{80}$Hg VISIBLE RADIATIONS EMITTED BY G.E.C. COLD CATHODE LAMP.

Line	Standard Wavelength Unit = 10^{-10}m (or 1Å)	Practical Wavelength	
		Unit = 10^{-10}m	Unit = 10^{-6}in.*
λ_1 (yellow)	5790·6633	5790·6931	22·798044
λ_2 (yellow)	5769·5990	5796·6286	22·715113
λ_3 (green)	5460·7535	5460·7816	21·499177
λ_4 (blue)	4358·3377	4358·3603	17·158929
λ_5 (violet)	4077·8383		
λ_6 (violet)	4046·5716		

* Based on conversion factor 1 m. = 39·370147 in.

The values of the wavelengths of the spectral lines of $^{198}_{80}$Hg emitted by the cold cathode lamps have been determined to the nearest 0·0001 Å by the National Physical Laboratory and are given in Table 2. The "standard wavelengths" are the values in dry air at 15 degs. C. and 760 mm. pressure, containing 0·03 per cent by volume of carbon dioxide and are referred to the internationally accepted value of 6438·4696Å for the red line of cadmium. The "practical values" are the values in air, at 20 degs. C. and 760 mm. pressure, containing water vapour at 7 mm. pressure (40 per cent relative humidity) and the normal amount of 0·03 per cent by volume of carbon dioxide.

$^{198}_{80}$Hg LAMPS AS STANDARD SOURCES

As mentioned above, the wavelength of cadmium red radiation, emitted by a Michelson Lamp under carefully controlled conditions is the present standard of length and, although this line is of high purity for a naturally occurring element, its width is greater than that of the $^{198}_{80}$Hg lines. The measurement of interferograms produced in cadmium red radiation over large retardations presents great practical difficulties, and the superiority of the $^{198}_{80}$Hg lamp

can be judged from the patterns shown in fig. 3. For this reason, great interest has been aroused in the possibility of establishing the green $^{198}_{80}Hg$ line as the primary reference line. To obtain the fullest advantage of this change, the maximum source luminosity and minimum line width are the most important factors, the cost of the lamp and associated operating gear being secondary considerations. On this basis, an electrodeless discharge lamp excited at a high frequency has considerable advantages over the cold cathode lamp. The type of electrodeless lamp shown in fig. 4 was originated by the National Bureau of Standards of America,[7] and is made from a length of 5 mm. bore borosilicate glass. The lamp contains 1·0 mg. of $^{198}_{80}Hg$ and argon, at a pressure of 3 mm. of mercury, as the carrier gas. In one method of operation, shown in fig. 4, the lamp is mounted in a coaxial water jacket and capacitively coupled to the output of a 100 watt, 100 Mc/s. oscillator by means of two electrodes clamped to the outside of the water jacket.

An alternative method of excitation, which has been suggested by American workers,[8] is to mount the lamp in a resonant cavity built into a wave guide system energised by a 3,000 Mc/s. continuous wave magnetron. Their investigations have shown that the intensity of the green 5,461 Å mercury line at this higher frequency is increased more than sixteenfold over its value at 100 Mc/s, the same excitation power being used in both cases.

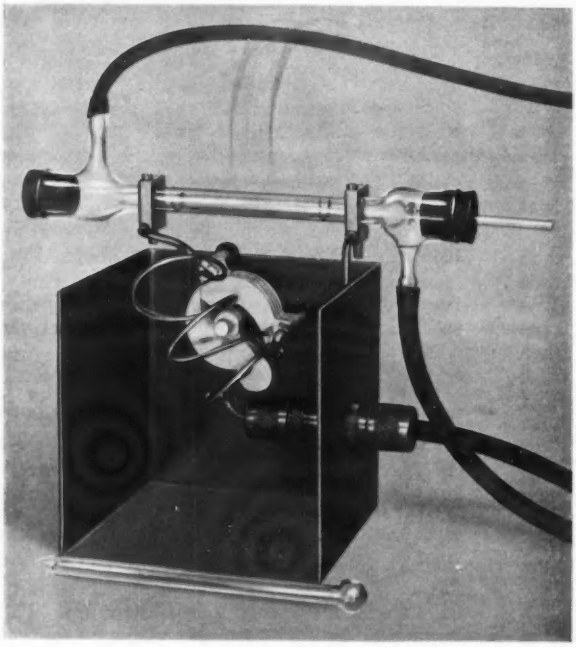


Fig. 4.—Electrodeless $^{198}_{80}Hg$ discharge lamp mounted for excitation at a frequency of 100 Mc/s. A separate discharge tube is shown in the foreground.

FUTURE WORK.

Further work remains to be carried out on the method of coupling, frequency of excitation and gas filling pressure in order to achieve the optimum set of operating conditions consistent with an economical lamp life. A lamp containing only $^{198}_{80}Hg$ would be the ideal source for the metrologist, the effect of pressure broadening being reduced to a minimum under these conditions. Initial trials have proved that the vapour pressure of mercury is sufficiently high at normal ambient temperatures for a discharge to be initiated and maintained in a water-cooled electrodeless lamp containing no carrier gas when excited at a frequency of 100 Mc/s. Furthermore, interferometric investigation of the spectrum of this lamp has shown that the widths of the spectral lines are considerably reduced by omission of the carrier gas. The important factor of lamp life has, however, to be investigated before the practicability of such a source can be assessed.

It can be seen that the development of the $^{198}_{80}Hg$ lamp has opened up an entirely new field of research in special discharge lamps. Some experience has already been gained with a second source containing the krypton isotope $^{84}_{36}Kr$, which has been separated electromagnetically in a mass spectrograph[9] by Dr. J. Koch, of the Universitetets Institut for Teoretisk Fysik, Copenhagen. Owing to the low boiling point of krypton, —153 degs. C., the $^{84}_{36}Kr$ lamp can

be operated with the positive column cooled in liquid air. This reduces the factor $\sqrt{\frac{T}{M}}$, which controls the Doppler broadening effect, to a value slightly below that for $^{198}_{80}Hg$ operated at a temperature of, say, 15 degs. C. Secondly, krypton does not exhibit the phenomenon of self-reversal so that a more intense source can be obtained by axial viewing of the horizontal limb of an H-form lamp. A $^{84}_{36}Kr$ lamp, either of a hot cathode type for A.C. operation or of an electrodeless form for high frequency excitation, therefore forms a possible alternative source for producing the reference spectral line.

The krypton and mercury isotope sources are now both being developed to determine the optimum operating conditions for each type. When these conditions have been established the lamps will be compared interferometrically to determine their ranges of application and suitability as length standards.

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TECHNICAL LITERATURE

A DIGEST OF RECENT BOOKS, ARTICLES AND PAPERS, BY MEMBERS OF THE G.E.C. AND ITS ASSOCIATED COMPANIES.

THE BEHAVIOUR OF NICKEL-CHROMIUM - IRON ALLOYS IN CARBON-BEARING GASES IN THE RANGE 900 degs.-1,000 degs. C. (431).

By D. M. Dovey and I. Jenkins (Research Laboratories).

Jour. Inst. Metals, Vol. 76, Part 6 (1950).

An investigation is reported into the cause of corrosion of nickel-chromium electrical-resistor alloys used at temperatures of 900 degs.-1,000 degs. C. in an atmosphere of partially burnt town's gas. The corrosion, which is shown to be due to simultaneous carburisation and oxidation of the alloy, with rapid intergranular oxidation in depth, is typical of that known as "green rot." The order of attack is less in alloys containing iron, and the presence of approximately 2 per cent silicon in an alloy is sufficient to suppress the corrosion completely.

The possible factors governing the corrosion mechanism are discussed, and the importance of the oxide layer as a barrier to carbon entry into the matrix is demonstrated.

THE ACTION OF WATER AND OF SULPHUR DIOXIDE ON GLASS SURFACES (432).

By R. W. Douglas and J. O. Isard (Research Laboratories).

Trans. Soc. Glass Techn., Vol. 33, pp. 289-335 (1949).

The removal of alkali from glass by the reaction with water or with sulphur dioxide has been investigated theoretically and experimentally. Both these reactions have been shown to be controlled by diffusion processes within the glass. The type of diffusion process involved is governed by the condition that the electrical neutrality of the glass must be maintained.

CONTROLLED ATMOSPHERES: PRINCIPLES AND APPLICATIONS IN THE FERROUS FIELD (433).

By D. M. Dovey and I. Jenkins (Research Laboratories).

Iron and Steel, December (1949) and January, February, March (1950).

At some stage of their processing, most commercial metals and alloys undergo heat treatment during which the metal surface is in contact with hot gases within the heating chamber. Reactions between the metal and the furnace gases may react adversely on the surface properties of the heat-treated material. To reduce such effects to the minimum, some measure of control over the reactions promoting them must be obtained. This in turn necessitates control over the composition of the atmosphere surrounding the metal during heat treatment. A mixture of gases of controlled composition is therefore generated and fed into the furnace chamber so as to displace completely the natural atmosphere. The relative concentrations of the active components of the generated atmosphere are such that metal-gas reactions are either suppressed or promoted according to requirements.

CORRECTION FACTORS FOR SLOTTED MEASURING LINES AT VERY HIGH FREQUENCIES (436).

By R. G. Medhurst and S. D. Pool (Research Laboratories).

Proc. I.E.E., Vol. 97, Part III, No. 48 (July, 1950).

The most important factor restricting the performance of slotted measuring lines at very high frequencies is likely to be the effect of mechanical irregularities on the probe pick-up, unless the line is unusually well constructed. These irregularities set a lower limit to the standing-wave ratio which can be measured. Impedances giving rise to standing-wave ratios above this limit can be measured, though the effect of the irregularities reduces the accuracy. If the line is not disturbed, these irregularities will usually have a repeatable effect, and they can be compensated for by a simple multiplication, the multiplying factor varying with the position along the line but being constant for each position. It is shown how these correction factors may be derived.

CINEMA AUDITORIUM LIGHTING: AN INVESTIGATION ON THE LEVEL OF ILLUMINATION REQUIRED FOR SAFE MOVEMENT (438).

By J. S. Smyth (Research Laboratories).
Trans. Illuminating Eng. Soc. (London), Vol. 15, No. 3 (1950).

The provision of " safety " lighting in cinema auditoriums is a statutory requirement in this country. The safety lighting is kept alight throughout the performance, and the degree of illumination must be sufficient to allow the audience to leave the auditorium in safety. Also, since the safety lighting is most needed if the usual electricity supply should fail, it must be supplied from a separate source, usually a secondary battery. The first part of the investigations of a technical panel set up to study safety lighting is described.

MULTI-STATION V.H.F. COMMUNICATION SYSTEMS USING FREQUENCY MODULATION (439).

By W. P. Cole and E. G. Hamer (Research Laboratories).
Jour. Brit. I.R.E., Vol. 10, No. 7 (July 1950).

The reasons for the use of multi-station v.h.f. systems of communication are given, together with an historical survey of previous experiments on frequency modulated systems. The required performance of multi-station equipment is derived from that of the standard equipment normally used for a single-station scheme. One of the most important factors for such schemes is that the main carrier frequencies should be nearly identical, and the permissible difference of frequency is determined. Details of the particular type of equipment used for the initial experiments and for a complete installation are given.

THE X-RAY STRUCTURE OF SPECULUM ELECTRODEPOSITS (441).

By H. P. Rooksby (Research Laboratories).
Jour. Electrodepositors' Tech. Soc., Vol. 26 (1950).

X-ray investigations of speculum electrodeposits on copper are described. The speculum deposits, intended to contain approximately 42 per cent by weight of tin, are found to possess either a metastable cubic near-gamma crystal structure, or one closely approaching that of the hexagonal eta phase, Cu_6Sn_5. The incidence of a bright or dull finish is influenced by three factors, which are described in detail.

ELECTRICAL CONDUCTIVITY OF OXIDE CATHODE COATINGS (443).

By D. A. Wright (Research Staff of M.O. Valve Co., at the G.E.C. Research Laboratories).
Brit. Jour. Appl. Phys., Vol. 1, June, 1950.

Conductivity measurements on activated coatings give results similar to those of Vink and Loosjes. Their theory implies barium concentration of at least 10^{19} atoms/cm^3. Hall effect measurements indicate 10^{14} electrons/cm^3 at 1,100 degs.K, and free path 2×10^{-5} cm. This result may not in fact be inconsistent with the Vink-Loosjes theory. P-type conductivity is not encountered in well-activated coatings, and is a feature developing while drawing emission under non-activating conditions. It is due to oxidisable impurities in the coatings. Rapid poisoning or activating effects at low temperatures emphasise the importance of phenomena at surfaces, and it is suggested that these are associated with electron or hole movement rather than ion movement.

THE PACKING AND POROSITY OF GROG PARTICLES (444).

By T. S. Busby (Research Laboratories).
Trans. Soc. Glass Techn., Vol. 34, pp. 10-16 (1950).

The theoretical packing of grog particles is discussed and a method for measuring it is described. The porosity of grog grains is calculated by a mercury displacement method and values are given for the porosity of sillimanite and fine clay grogs.

AN " IDEAL " POST DEFLECTION ACCELERATOR CATHODE RAY TUBE (445).

By L. S. Allard (Research Laboratories).
Electronic Engineering, November, 1950.

A special design of cathode ray tube employing the post deflection acceleration technique has been investigated, which is completely free from scan distortions. This tube can give increased brightness at higher screen potentials with no increase in the deflecting voltages required.

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